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The Transfer Function of Quarry Blast Noise and Vibration into Typical Residential Structures

Kamperman Associates, Inc, Downers Grove, IL

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THE TRANSFER FUNCTION OF QUARRY BLAST NOISE AND VIBRATION INTO TYPICAL RESIDENTIAL STRUCTURES

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An experimental program was conducted to determine the transfer function of quarry blast noise and vibration into typical structures. Four distinct noise and vibration signals are produced inside nearby dwellings. It was determined that due to resonances excited within the dwellings, the noise and vibration excitation was greater inside the dwellings than outside.

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KAMPERMAN ASSOCIATES, INC.

under

CONTRACT 68-01-4134

for the

U.S. Environmental Protection Agency
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1.0 INTRODUCTION

This research program was designed to compare the exterior blast noise and vibration environment during a stone quarry blast with the blast noise and vibration environment produced inside typical nearby dwellings. It was found that in all cases the ground-borne vibration from a blast produced more noise and vibration inside than outside a dwelling. The typical air blast that follows shortly after the ground wave may produce even more noise and vibration inside than the excitation from the ground wave. A large choice of transfer functions was determined to compare the outdoor blast noise and ground vibration to the indoor noise and vibration for typical dwellings during a quarry blast.

1.1 Current Information Available on Quarry Blast Noise and Vibration

At the time this research program was initiated, the blast noise and ground vibration described by peak-over-pressure and peak ground velocity measurements were already well understood. The Bureau of Mines had published several reports containing data that described the relationship between these peak levels and the distance from the blast and the maximum charge per delay of the blast.[1,2] These data also showed that peak values correlated well with structural damage and window breakage. Time history and frequency spectra measurements have been made of blast noise and vibration inside and outside of dwellings by the Bureau of Mines[3] and Kamperman Associates Inc.[4] These data show that there are two separate waves outside (a ground-borne wave and an airborne wave) and each wave causes both sound and vibration signals within dwellings.

The effects of weather conditions on the airborne blast wave have also been researched previously.[3-5] At distances of several kilometers from the blast, the temperature gradient, wind speed and direction, and wind gradient greatly control the peak-overpressure. At lesser distances of a few kilometers the wind speed and direction are the most significant parameters in the propagation of the air blast beyond the quarry or open pit mine property.

Studies on the psychological effects of impulse signals such as quarry and open pit mine blasting have also been done previously.[7-10] The most recent reports on impulse noises suggest that a C-weighted 1-second integration of the sound wave may be used to describe the human reaction.[8,10] Human annoyance to vibration correlates well with peak velocities above 2 to 8 Hz (depending upon the direction) and peak acceleration below these frequencies. A frequency-weighted peak acceleration measurement has been proposed by ISO as an approximation to this.[9]

Only limited information has been published on reducing the noise and vibration from quarry and open pit mine blasting. However, this information does suggest that improved blasting techniques produce lower-level sound and ground velocity signals.[6]

1.2 Purpose of This Research Study

The purpose of this study was to determine the transfer function of the outdoor ground wave and air wave produced by a quarry blast to the indoor vibration and sound found in typical dwellings. The indoor vibration and sound were to be compared to accepted criteria descriptors of human annoyance produced by impulsive sound and vibration. The outdoor signals were to be compared to past measurement descriptors of quarry blasts. Schemes predicting the magnitude of the blast, given the distance from the blast and the maximum charge per delay, were also studied to better understand the overall blast noise and vibration phenomena.

The objective of this study was to research a very small segment of the overall problem of annoyance to residents inside typical dwellings arising from blasting activities at nearby stone quarries. Subjective responses of human annoyance to blasting were not considered in this study. Health and welfare considerations were explicitly excluded. The study concentrated only on determining simple, objective measures to monitor ground-borne vibration and airborne blast noise outside and predict the noise and vibration inside a typical dwelling. The indoor and outdoor blast noise and vibration descriptors were selected to be compatible with the physical descriptors currently being used by other organizations concerned with various aspects of blast noise and vibration phenomena. The organizations of principal concern were: EPA, ISO, BuMines, CERL, Department of the Army, AMRL/BBA at WPAFB and HUD. The results of the 1975 quarry blast noise study for Illinois IEQ are included with the results of this study for EPA.

2.0 SUMMARY

2.1 Blast Noise and Vibration Descriptors

Determining the transfer function for typical dwellings by measuring the outdoor blast noise and vibration and comparing it with the indoor blast noise and vibration can be accomplished in a variety of ways. The main concern of this study was to select descriptors that directly related to measurement methodologies already commonly in use, simple descriptors that would best describe the response of the dwelling to the blast noise and vibration, and descriptors that could measure the human annoyance caused by blast noise and vibration inside dwellings. The descriptors used are outlined in Tables 2.1-1 and 2.1-2.

Table 2.1-1. Blast Noise Descriptors

1. Peak sound pressure level.
2. Sound pressure time history.
3. Sound frequency spectrum analysis.
4. C-weighted sound exposure level (CSEL).
5. C-weighted sound-level slow meter response.
6. A-weighted sound exposure level (SEL) indoors.
7. A-weighted frequency spectra indoors.
8. 4 to 200 Hz sound exposure level (SEL).
9. 4 to 200 Hz slow meter response.

Note: SEL = sound exposure level, VEL = vibration exposure level, both normalized to one second.

Table 2.1-2. Vibration Descriptors

1. Peak velocity vibration level, lateral (radial), transverse, vertical.
2. Velocity vibration time history.
3. Vector sum of lateral, transverse, and vertical velocity exposure level (VEL).
4. Lateral, transverse, and vertical velocity vibration frequency spectrum analysis.
5. Lateral, transverse, and vertical independent velocity vibration exposure level (VEL).
6. Lateral, transverse, and vertical independent velocity vibration level slow meter response.
7. Lateral, transverse, and vertical independent velocity vibration level C-weighted slow meter response.
8. Peak acceleration level, 5.6 Hz low-pass.
9. 5.6 Hz low-pass acceleration VEL indoors.
10. Acceleration vibration frequency spectrum analysis (indoors).

Twenty-six blast events were recorded for this current study, which also covers an additional 15 blast events recorded by the Illinois IEQ study of 1975. The total 41 recorded blast events consist of the 18 blast events recorded by Kamperman Associates Inc. and Mr. Greg Zak of Illinois EPA, plus an additional 8 by Illinois EPA for this study, and 15 blast events recorded in 1975 in the

Illinois IEQ study by a combination of Bureau of Mines, Kamperman Associates Inc. and Illinois EPA.

All the descriptors in Tables 2.1-1 and 2.1-2 were used to evaluate the blast noise and vibration signals from 10 to 15 of the blast events recorded in this study.

2.2 Blast Noise and Vibration Measurement Methodologies

Three different measurement systems were utilized to record the information summarized in this report. The principal measurement system was a semi-portable (mobile) tape-recording system that permitted simultaneous recording of eight channels of information over a frequency range of 0 to 2500 Hz, plus a secondary cassette recorder used to obtain the A-weighted sound level inside a dwelling over a frequency range of 25 to 10 K Hz. Three identical velocity-sensitive transducers were used to monitor the ground vibration outside a dwelling. The velocity pickups were oriented in the three mutually perpendicular axes to measure lateral, transverse, and vertical ground velocity. Two microphone carrier systems, one located outside the dwelling and one inside, were used to measure the air blast noise from 0.1 to 2.5 K Hz. Similarly, the indoor floor vibration was monitored with three mutually perpendicular mounted velocity transducers identical to the units used outside the dwelling. Velocity was recorded from these units over a frequency range of 4 to 1,000 Hz. Occasionally one of the indoor transducers would be replaced by an accelerometer with an extended frequency range of 0.5 to 2,500 Hz.

The second measurement system was a portable air blast tape-recording system handled by Greg Zak of Illinois EPA. This system was designed to record the total air blast signal ranging from 0.6 Hz to 2,000 Hz. The portable blast noise recording system was used to record the blast noise on the quarry property on a line between the blast event and the instrumented dwelling. In addition, Mr. Zak was able to record blasts from an open pit coal mine, two silica sand quarries, and an additional limestone quarry.

The air blast study conducted in 1975 for Illinois IEQ utilized two principal measuring systems to record the air blast signal on magnetic tape. The two systems had the same capability as the portable system used by Illinois EPA and described in the previous paragraph. Mr. Greg Zak of Illinois EPA supplemented the blast noise measurements made by Kamperman Associates Inc. in the same manner for both the 1975 and the 1976 blast noise studies.

The third type of measurement system was operated by the Bureau of Mines. The Bureau of Mines provided a mobile van with personnel under the direction of David Siskind from the Twin Cities Research Center to augment the 1975 Illinois IEQ study. The Bureau of Mines had the capability of recording up to 12 channels of ground-borne and airborne blast data simultaneously. The Bureau of Mines made two separate visits to the Chicago area to measure blast noise and vibration inside and outside residential structures during the 1975 study. The results of their data have been published[3] and are incorporated into the findings of this study.

All the blast noise and vibration measurements made during the 1975 Illinois IEQ study and the 1976 EPA study were obtained at limestone quarries in the Chicago area, with the exception of the eight additional air blast recordings made by Greg Zak of Illinois EPA.

2.3 Data Reduction Methodologies

The mobile recording system assembled by Kamperman Associates Inc. for this study was designed to derive all of the descriptors listed in Tables 2.1-1 and 2.1-2 for the 18 blasts recorded in typical dwellings instrumented both inside and outside. The methodologies used to obtain the comprehensive information from these recordings are contained in Appendix A of this report.

2.4 Selection of Descriptors of Human Annoyance

The annoyance to the residents inside dwellings resulting from blasting activities is, indeed, a very complex problem. Over the years, the Bureau of Mines has been principally concerned with establishing safe limits for air blast and ground vibration to avoid structural damage to nearby buildings during a blast. With the recently increasing population density in the vicinity of quarries and open pit mines, annoyance to residents inside dwellings during blasting activities is receiving much more attention and study. There are no recognized annoyance standards applicable to blasting at this time. Whether the peak noise or vibration is more or less significant than the total energy in the blast event is subject to debate. It is for this reason that both peak- and energy-type blast noise and vibration descriptors were utilized in this study (Tables 2.1-1 and 2.1-2).

2.5 Determining the Transfer Function for Blast Noise and Vibration from Outside to Inside Typical Dwellings

Because of the uncertainties associated with human response to blasting events discussed in the previous section, it was believed important to consider many descriptors (see Tables 2.1-1 and 2.1-2) to arrive at a variety of transfer functions. This wide variety permits the user of this study to select the blast noise and vibration descriptors which best meet his needs, and then to select the transfer function from the outdoor blast noise and vibration environment and relate it to the indoor blast noise and vibration environment for the dwellings studied.

2.6 Relating the Magnitude of Blast Noise and Vibration to Quarry Blasting Techniques

The blast noise level (using different descriptors) was correlated with the maximum explosive charge weight per delay. A similar correlation was made for the ground vibration. Both the air blast and the ground-borne vibration were then correlated with distance from the blast.

3.0 CONCLUSIONS AND RESULTS OF STUDY

3.1 Frequency Range of Interest

More than 200 detailed blast noise and vibration frequency spectra were studied in detail to determine the frequency range of interest with respect to typical dwellings. Different criteria were established to measure the air blast and ground-borne vibration from a quarry blast.

The ground vibration velocity level spectra measured outside (in each of the three mutually perpendicular planes) were compared with similar floor vibration velocity levels measured inside a specific dwelling. Every dwelling measured contained some resonances that produced higher vibrations, at certain frequencies, inside the dwelling than outside in the ground. The frequency bandwidth containing these resonant frequencies (vibration amplification) was noted for each dwelling. A composite of all of the data showed that a measurement bandwidth of approximately 5 to 200 Hz would encompass all of the dwelling resonances due to ground-borne vibration. The majority of the resonances were between 10 and 100 Hz.

A slightly different approach was taken in measuring the interior vibration caused by the air blast signal. The major blast energy produced by stone quarry blasting appears at 1 Hz (± 0.5 Hz). At this frequency of maximum pressure, the magnitude of the 1 Hz component is essentially the same inside and outside the dwelling. However, typical single-family dwellings do not respond to this 1 Hz component. Therefore, the high amplitude 1 Hz component was considered relatively unimportant to the residents within dwellings, since they could not hear or feel it. The next step was to look at all the floor vibration (velocity) level spectra generated by the air blast alone. It was decided that the vibration frequency range of interest would be the measured velocity level bandwidth that was exactly 20 dB below the peak velocity within the bandwidth. After summarizing all the results, it was found that the bandwidth meeting this criteria was again approximately 5 to 200 Hz, with the majority of the measurements falling between 10 and 100 Hz.

The conclusion is that typical dwellings contain numerous resonant frequencies throughout the frequency range from 5 to 200 Hz. These resonances can be readily excited during a blast by either the ground-borne wave or the air wave.

3.2 Amplitude Measures of Blast Noise and Vibration

Two basic signal amplitude measurement methodologies were used in this study: the peak level of the blast noise or vibration and a 1-second equivalent integration of the blast noise or vibration exposure level (SEL or VEL). The standard (type 1) sound-level meter set for slow meter response was also utilized to approximate the true 1-second integration of SEL or VEL. Sound-level meters with a 1-second time constant are a standardized instrument in common use. One-second SEL or VEL instruments have been built, but are not in common use at this time.

3.3 Human Annoyance Descriptors Applied Inside a Dwelling

There are four signals of major interest inside a dwelling for each blast event: the noise and vibration produced by the ground wave, which arrives first, and the noise and vibration produced by the air blast, which follows shortly after.

Two noise measures appear appropriate, since they can best be related to previous annoyance studies. These are the C-weighted SEL (CSEL) and the A-weighted SEL. The C-weighted SEL can be correlated in a straightforward manner with the magnitude of the structural vibration of the dwelling resulting from the blast. The A-weighted SEL can be used to measure non-linear effects such as rattling of windows, dishes, or bric-a-brac, and effects on the actual structure of the dwelling.

The non-linear rattling effects are known to occur especially in cases where the blast noise and vibration are relatively intense. The prime objective of this study was to determine the transfer function of outdoor noise and vibration to the indoor noise and vibration. To accomplish this, most measurements were made at a distance of approximately 1000 meters from the blast to enable one to separate the arrival of the ground wave from the later arrival of the air blast. In a few situations there were homes located 1/10 of this distance from the blast event; when this occurred, an instrumented home 1000 meters from the blast event did not usually receive sufficient excitation from either the ground wave or the air blast to cause significant rattling-type noise inside the dwelling because the blasting levels were limited by the nearest residence.

A third descriptor for measuring the indoor blast noise might logically be the peak pressure level. It was pointed out earlier that the peak pressure level is essentially the same inside and outside a typical dwelling.

Considerable study has been done on the response of humans to low-frequency vibration. In the principal frequency range of interest to this program (5 to 100 Hz), there appears to be a general consensus that humans are velocity-sensitive. It is not understood whether peak velocity level or the vibration exposure level (VEL) is the important descriptor. It has been pointed out on numerous occasions that the peak velocity level from slamming a door in a dwelling may be equal to that produced by a quarry blast. This was tested and found to be true. However, the slamming door event had a duration of only 0.01 seconds, while the typical blast events reported in this study had an average duration of approximately 5 seconds (including the air blast) or 500 times longer.

3.4 The Rank Ordering of Outdoor Blast Noise and Vibration Descriptors That Correlate Best with the Indoor Human Annoyance Descriptors

Four categories must be considered: (1) the outdoor ground vibration as it relates to the indoor floor vibration; (2) the outdoor ground vibration as it relates to the indoor noise caused by the vibration; (3) the outdoor air blast as it relates to the indoor noise; (4) the outdoor air blast as it relates to the indoor floor vibration. A large number of descriptors were analyzed and the results are presented in this section. A variation of less than 2:1 in the standard deviation is probably not significant due to the limited data base, which ranged between 10 and 30 data pairs (typically 15). The following is an abbreviated summary starting with the first category (see Table 3.4-1). Good correlation (item 3 in the table) was found by determining the VEL of the velocity vector sum of the lateral, transverse, and vertical components outside and relating it to the similar VEL of the three components on the floor of the dwelling inside (standard deviation 2.6 dB). A much simpler measurement (items 5 and 6) can be made by simply utilizing one velocity pickup (with a uniform response down to 4 to 6 Hz) and connecting it to the input of a standard sound-level meter set for flat frequency response (down to at least 5 Hz) and slow meter response. The velocity

Table 3.4-1. Rank ordering (by standard deviation) of outdoor measurement of ground velocity minus indoor measurement of floor velocity

	Outdoor Ground Velocity (dB re 1 meter per second)	Indoor Floor Velocity Due to Ground Wave (dB re 1 meter per second)	Mean Difference	Standard Deviation
1.	Vector Sum 4-200 Hz VEL	Vertical 4-200 Hz VEL	+2.3	2.1
2.	Maximum Peak of 3 Directions	Maximum Peak of 3 Directions	-2.2	2.5
3.	Vector Sum 4-200 Hz VEL	Vector Sum 4-200 Hz VEL	-1.3	2.6
4.	Vertical 4-200 Hz VEL	Vertical 4-200 Hz VEL	-4.7	2.8
5.	Vertical 4-200 Hz Slow Response	Vertical 4-200 Hz VEL	-7.0	2.9
6.	Lateral 4-200 Hz Slow Response	Vertical 4-200 Hz VEL	-3.9	2.9
7.	Maximum 4-200 Hz VEL	Maximum 4-200 Hz VEL	+1.0	2.9
8.	Lateral 4-200 Hz VEL	Vertical 4-200 Hz VEL	-1.4	3.1
9.	Lateral Peak	Vertical Peak	-2.2	3.2
10.	Lateral 4-200 Hz VEL	Lateral 4-200 Hz VEL	+0.8	3.4
11.	Transverse 4-200 Hz VEL	Transverse 4-200 Hz VEL	+0.6	3.4
12.	Lateral 4-200 Hz VEL	Vector Sum 4-200 Hz VEL	-4.8	3.4
13.	Maximum Peak	Vertical 4-200 Hz VEL	+9.3	3.4
14.	Lateral Peak	Lateral Peak	-0.3	3.4
15.	Vertical 4-200 Hz Slow	Maximum 4-200 Hz VEL	+7.6	3.7
16.	Vertical 4-200 Hz Slow	Vector Sum 4-200 Hz VEL	-10.8	3.9
17.	Lateral 4-200 Hz Slow	Maximum 4-200 Hz VEL	+4.1	3.9
18.	Vertical Peak	Vertical Peak	-4.1	4.0
19.	Transverse Peak	Transverse Peak	+0.1	4.0
20.	Lateral 4-200 Hz Slow	Vector Sum 4-200 Hz VEL	-7.1	4.2
21.	Vertical C-Wt. Slow	Vertical 4-200 Hz VEL	-10.1	5.3
22.	Lateral C-Wt. Slow	Vertical 4-200 Hz VEL	-8.3	5.6
23.	Lateral C-Wt. Slow	Vector Sum 4-200 Hz VEL	-11.8	7.3

pickup should measure horizontal ground vibration in the lateral (radial) or vertical direction. The maximum reading on the sound-level meter would correlate well with the VEL of the vertical velocity of the floor inside the dwelling (standard deviation of 2.9 dB). If one is interested in the peak velocity level in any of the three directions on the floor inside the dwelling, one should measure in all three directions on the ground outside (2). The maximum peak level on the ground outside correlates with the maximum peak level on the floor inside (standard deviation 2.5 dB). The peak vector sum level of the three mutually perpendicular axes measuring the ground outside would also be expected to correlate with the peak vector sum level on the floor inside (standard deviation between 2 and 3 dB), although this was not experimentally proven because of the difficulties of computing the vector sum electrically from tape-recorded signals. The simplest method for determining the peak level of the vertical velocity inside is to measure the peak level of the lateral (radial) ground velocity (9) outside the dwelling (standard deviation 3.2 dB).

The second category relates the ground velocity vibration level outside to the noise generated inside a typical dwelling (see Table 3.3-2). A measurement of the lateral (radial) ground velocity vibration level (item 1) with a flat response sound-level meter (5 Hz and above) and observing the peak reading on slow meter gave good correlation to the indoor C-weighted SEL (CSEL) (standard deviation 2.1 dB). The VEL of the vector sum (3) measured on the

Table 3.4-2. Rank ordering (by standard deviation) of measurements of outdoor ground velocity level minus indoor sound pressure level.

Outdoor Ground Velocity Level (dB re 1 meter per second)	Indoor Sound Pressure Level Due to Ground Wave (dB re 20 μ pascals)	Mean Difference	Standard Deviation
1. Lateral 4-200 Hz Slow	C-Wt. SEL	-149.9	2.1
2. Lateral 4-200 Hz VEL	C-Wt. SEL	-147.5	2.6
3. Vector Sum 4-200 Hz VEL	C-Wt. SEL	-143.8	3.2
4. Lateral 4-200 Hz VEL	4-200 Hz SEL	-153.2	3.2
5. Vector Sum 4-200 Hz VEL	4-200 Hz SEL	-150.3	3.3
6. Transverse 4-200 Hz VEL	4-200 Hz SEL	-154.6	3.5
7. Vertical 4-200 Hz Slow	C-Wt. SEL	-153.2	3.6
8. Lateral Peak	C-Wt. SEL	-137.2	3.6
9. Vertical 4-200 Hz VEL	C-Wt. SEL	-150.9	3.8
10. Lateral C-Wt. Slow	C-Wt. SEL	-154.5	3.9
11. Vertical 4-200 Hz VEL	4-200 Hz SEL	-156.7	4.2
12. Vertical 4-200 Hz Slow	4-200 Hz SEL	-159.8	4.5
13. Transverse 4-200 Hz VEL	C-Wt. SEL	-149.0	5.0
14. Lateral Peak	Peak	-156.0	5.4
15. Transverse Peak	Peak	-157.1	5.7
16. Vertical C-Wt. Slow	C-Wt. SEL	-163.1	5.7
17. Vertical Peak	Peak	-158.1	6.6

Example: (1) A lateral ground vibration, maximum reading and slow response on a sound-level meter, of -50 dB re one m/s (0.12 in/s) would produce an indoor noise level of 100 dB CSEL.

ground outside was correlated with the CSEL inside (standard deviation of 3.2 dB). To determine the peak noise level inside (14), one can measure the peak lateral (radial) velocity vibration level in the ground outside (standard deviation 5.4 dB).

The third category deals with the blast noise outside as it relates to the noise generated inside (see Table 3.3-3). Good correlation was obtained by inserting a 4 to 200 Hz filter into the external filter connections on a type 1 sound-level meter (2) and observing the maximum response with the slow meter response. This related to the CSEL inside (standard deviation 2.5 dB). Another choice is to use a standard type 1 precision sound-level meter set on C-weight slow meter response (3) and read the maximum outside level to approximate CSEL inside (standard deviation 2.7 dB). An alternate choice is to measure CSEL outside (4) re CSEL inside (standard deviation 2.7 dB). The SEL measured over the frequency range of 4 to 200 Hz outside correlated (5) with the CSEL inside (standard deviation 3.5 dB). No measurement outside correlated very well with the A-weighted noise level inside. The standard sound-level meter on C-weight slow response max reading (9) correlated with the indoor A-weighted SEL (standard deviation 6.5 dB).

The fourth category deals with the relationship between the outdoor air blast and the indoor floor vibration (see Table 3.3-4). In this situation, an external 4 to 200 Hz 4-pole (24 dB/octave) band-pass filter on a standard type 1 precision sound-level meter

Table 3.4-3. Rank ordering (by standard deviation) of measurements of outdoor sound pressure level minus indoor sound pressure level.

Outdoor Sound Pressure Level (dB re 20 µ pascals)	Indoor Sound Pressure Level Due to the Air Wave (dB re 20 µ pascals)	Mean Difference	Standard Deviation
1. Peak	Peak	-0.9	1.6
2. 4-200 Hz Slow	C-Wt. SEL	11.3	2.5
3. C-Wt. Slow	C-Wt. SEL	2.8	2.7
4. C-Wt. SEL	C-Wt. SEL	4.3	2.7
5. 4-200 Hz SEL	C-Wt. SEL	16.4	3.5
6. 4-200 Hz SEL	4-200 Hz SEL	-0.5	3.6
7. Peak	C-Wt. SEL	32.9	4.8
8. 4-200 Hz SEL	A-Wt. SEL	46.3	5.4
9. C-Wt. Slow	A-Wt. SEL	32.9	6.5
10. C-Wt. Slow	A-Wt. SEL	34.9	6.5
11. C-Wt. SEL	A-Wt. SEL	35.3	6.7

Table 3.4-4. Rank ordering (by standard deviation) of measurements of outdoor sound pressure level minus indoor floor velocity level.

Outdoor Sound Pressure Level (dB re 20 μ pascals)	Indoor Floor Velocity Level Due to Air Wave (dB re 1 meter per second)	Mean Difference	Standard Deviation
1. 4-200 Hz Slow	Vector Sum 4-200 Hz VEL	166.0	2.9
2. C-Wt. SEL	Vector Sum 4-200 Hz VEL	160.1	3.6
3. C-Wt. SEL	Maximum 4-200 Hz VEL	161.7	3.6
4. C-Wt. Slow	Vector Sum 4-200 Hz VEL	157.6	3.8
5. C-Wt. SEL	Vertical 4-200 Hz VEL	163.3	4.6
6. 4-200 Hz Slow	Vertical 4-200 Hz Slow	178.2	4.7
7. 4-200 Hz Slow	Maximum 4-200 Hz VEL	168.9	5.0
8. 4-200 Hz SEL	Maximum 4-200 Hz VEL	173.6	5.2
9. 4-200 Hz SEL	Maximum Peak	162.4	5.2
10. Peak	Maximum Peak	178.2	5.2
11. Peak	Vector Sum 4-200 Hz VEL	186.8	5.3
12. 4-200 Hz Slow	Maximum Peak	157.8	5.8
13. 4-200 Hz SEL	Transverse 4-200 Hz VEL	184.2	6.0
14. 4-200 Hz Slow	Vertical 4-200 Hz VEL	169.0	6.2
15. C-Wt. Slow	Maximum Peak	149.1	6.2
16. Peak	Transverse Peak	188.9	6.3
17. C-Wt. SEL	Maximum Peak	152.3	6.4
18. C-Wt. Peak	Maximum Peak	163.6	6.6
19. 4-200 Hz SEL	Vector Sum 4-200 Hz VEL	173.5	7.3
20. 4-200 Hz SEL	Vertical 4-200 Hz VEL	176.1	7.8
21. C-Wt. Slow	Vertical 4-200 Hz VEL	153.6	7.8
22. Peak	Vertical 4-200 Hz VEL	190.1	8.1
23. Peak	Vertical Peak	180.7	8.3
24. Peak	Lateral Peak	185.7	8.5
25. 4-200 Hz SEL	Lateral 4-200 Hz VEL	180.4	9.1

Example: (2) An outdoor blast of 100 dB CSEL would shake a dwelling floor at -60 dB VEL re one m/s.

Example: (15) An outdoor blast of 100 dB C-weighted maximum slow meter response would shake a dwelling floor at -49 dB re one m/s (equal to 0.14 in/s).

on slow response read outside, correlated well (1) with the vector sum of the velocity VEL of the floor velocity inside (standard deviation 2.9 dB). Another choice was CSEL outside (2) relative to the vector sum 4 to 200 Hz velocity VEL inside (standard deviation 3.6 dB). The simplest measurement was to use the standard C-weight slow response precision sound-level meter outside (4) to relate to the vector velocity VEL of the floor vibration inside (standard deviation 3.8 dB). It was interesting to find that the SEL of the outdoor air blast measured in the bandwidth of 4 to 200 Hz (18) compared with the vector sum VEL over the same frequency range for the floor velocity gave a rather wide standard deviation of 7.3 dB.

The peak sound pressure level outside compared (9) to the maximum peak velocity level in any direction on the floor inside gave a standard deviation of 5.2 dB. The peak sound pressure level outside correlated (10) with the indoor floor velocity vector sum VEL for a standard deviation of 5.3 dB.

3.5 Comparison of Outdoor Air Blast Descriptors

It has been common practice to describe blast noise in terms of the peak-over-pressure in the air. Table 3.5-1 shows how different outdoor blast noise measurement descriptors relate to each other. All air blasts recorded for the EPA study are included in this table.

Table 3.5-1. Comparison of outdoor air blast descriptors (descriptor A minus descriptor B). Sound levels in dB re 20 µ pascals.

Descriptor A	Descriptor B	Mean Difference	Standard Deviation
Peak Sound Level	C-Weighted SEL	25.6	5.8
Peak Sound Level	C-Weighted Slow Meter	27.3	5.7
Peak Sound Level	4-200 Hz SEL	16.3	3.8
Peak Sound Level	4-200 Hz Slow Meter	19.9	4.6
4-200 Hz SEL	C-Weighted SEL	8.6	4.2
4-200 Hz SEL	C-Weighted Slow Meter	10.4	4.2
C-Weighted SEL	C-Weighted Slow Meter	1.7	2.1
4-200 Hz SEL	4-200 Hz Slow Meter	3.6	2.2

3.6 The Importance of the One Hertz Air Blast Peak

Four blast events were recorded with an accelerometer mounted directly on top of a velocity transducer. Both transducers were oriented to measure vertical floor motion. The purpose of this experiment was to confirm that the air blast with its very strong 1 Hz (± 0.5 Hz) frequency component had little influence on the response of typical dwellings. Table 3.6-1 contains the results of the ISO[7] draft recommendation (5.6 Hz low-pass filter) acceleration measurement experiment. VEL was used instead of peak acceleration as recommended by ISO. For the purpose of this discussion either peak or VEL is satisfactory. The large number of floor velocity frequency spectra measured and analyzed showed that a typical dwelling did not respond to an air blast below approximately 5 Hz. The "typical dwelling" referred to throughout this report is a single-family one- or two-story structure with a basement. Table 3.6-1 shows that increasing the measurement bandwidth to frequencies below 4 Hz (to 0.5 Hz) had little effect on the measured floor vibration (except for blast no. 14) even though the air blast is most intense at 1 Hz. Thus, for typical dwellings, the ISO frequency-weighted acceleration measurement is equivalent to a velocity measurement where one meter per second squared (frequency weighted) equals 1.1 inches per second velocity.

The data in Table 3.6-1 include only the air blast portion of the blast event. The ground wave does not contain blast energy below 5 Hz.

Table 3.6-1 Integrated energy of vertical floor acceleration according to ISO recommendations with further frequency filtering.

Filter Bandwidth	Blast No. 14*	15	16	17
	dB re 1 g VEL			
0.5 Hz - 1000 Hz	-66.0	-	-	-
0.5 Hz - 50 Hz	-66.0	-56.5	-65.4	-69.0
1 Hz - 50 Hz	-66.8	-56.7	-65.4	-69.0
2 Hz - 50 Hz	-68.4	-57.4	-65.4	-69.0
4 Hz - 50 Hz	-72.6	-57.5	-65.4	-69.0
5 Hz - 50 Hz	-73.0	-57.5	-65.4	-69.0
5 Hz - 100 Hz	-73.0	-	-65.4	-69.0

*Note that blast no. 14 was measured in a large, stiff concrete structure more typical of a dormitory, office, or concrete apartment building than of a single-family dwelling.

Blast no. 14 was recorded on the second floor of a two-story concrete office building with exterior plan dimensions of nearly 100 meters. None of the blast 14 test results were included in the transfer function comparisons in Tables 3.3-1 through 3.3-4. The test results obtained from the concrete office buildings were very different from the results obtained from the single-family dwellings, as Table 3.6-1 shows. It is clear that an air blast would have greater impact on large, stiff (concrete or block) structures such as domitories, hotels and hospitals.

3.7 Predicting the Amplitude of Quarry Blast Noise and Vibration

The peak velocity level of the ground wave correlates to the distance and maximum explosive charge by the relationship

$$20 \log v = 20 \log H + 20 (\beta) \log \left(\frac{D}{W^{1/2}}\right)$$

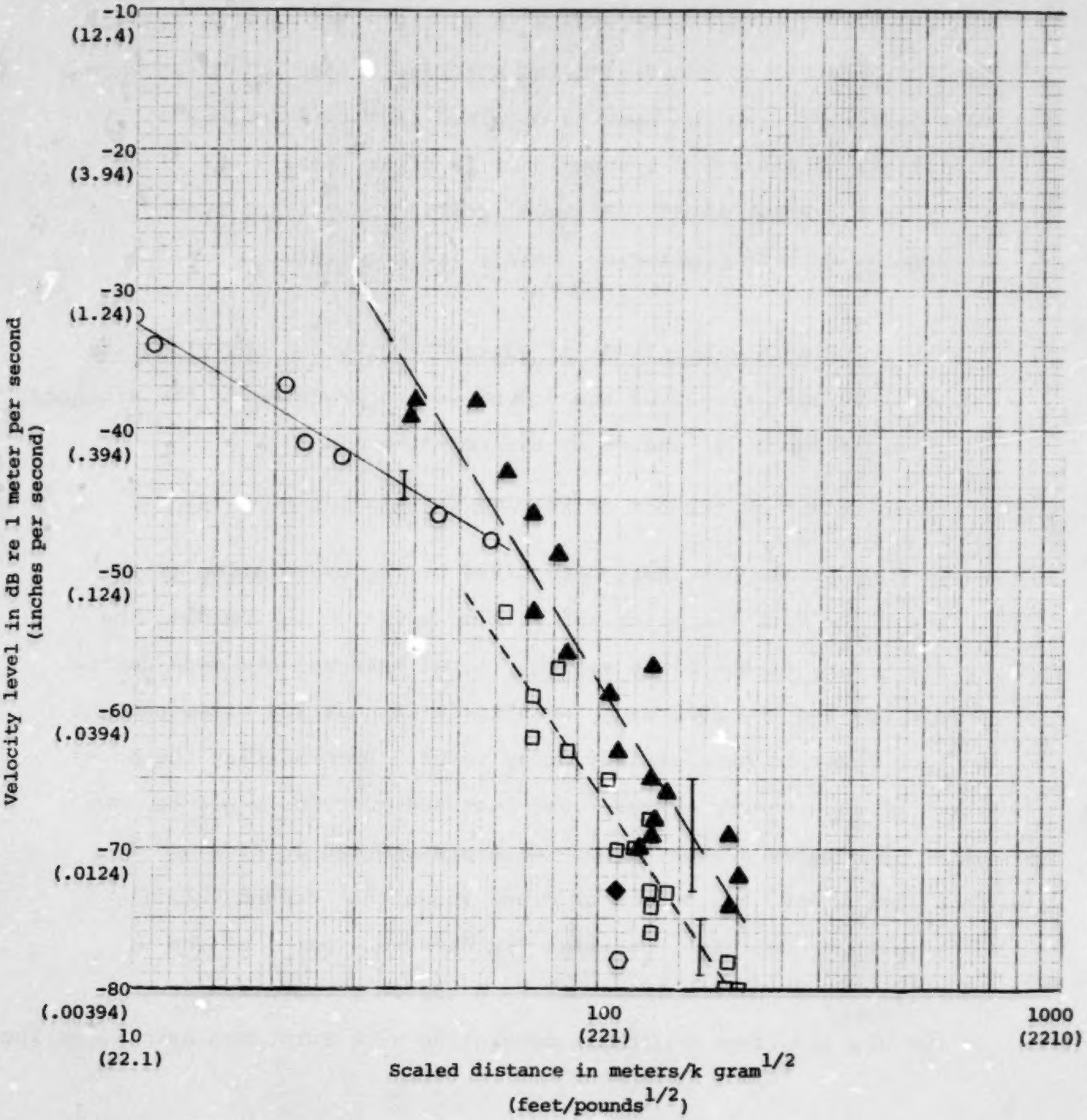
where H and β are constants determined by the orientation of the face and the rock formation and soil composition surrounding the quarry. Many of the blast velocity level measurements made during this study and the 1975 study were taken at quarries close enough to each other to have similar decay rates. By examining the decay rates of each quarry it was found that the quarries could be combined into three groups. These data are plotted in Fig. 3.7-1. In Bulletin 656, the Bureau of Mines shows that ground velocity data taken at different quarries (in different parts of the country) cannot be combined to form a ground propagation law. In the six limestone quarries cooperating with Kamperman Associates Inc.

Fig. 3.7-1. Velocity Levels versus Scaled Distance

Quarry group 1: ○ — Peaks

Quarry group 2: ▲ — Peaks, □— 4-200 Hz VEL

Quarry group 3: ◆ — Peaks, ⬡— 4-200 Hz VEL



for blast measurements, it was found that quarries very near to one another (within a few kilometers) did have the same propagation rate but those separated by several kilometers had quite different propagation rates. The data in Fig. 3.7-1 were, therefore, separated into three groups of quarries. Only peak ground velocity level was measured in group 1. Both peak and 4 to 200 Hz vector summed VEL ground velocities were measured in groups 2 and 3, but only one shot was measured in group 3. The ground velocity level data from group 2 show that the line describing the 4 to 200 Hz ground velocity vector sum VEL is parallel to the line describing the peak ground velocities from the same group, but lies approximately 8 dB lower. The error bar shown for the vector sum VEL data is smaller than the error bar (standard deviation) shown for the peak ground velocity level data.

The peak sound pressure level (P) can be correlated with the ratio of the distance from the blast (D) divided by the cube root of the maximum explosive charge per delay (W). This correlation can be expressed as

$$20 \log P = 20 \log K + 20 (\beta) \log \left(\frac{D}{W^{1/3}}\right)$$

where K and β are constants depending on the orientation of the face and the particular weather conditions.

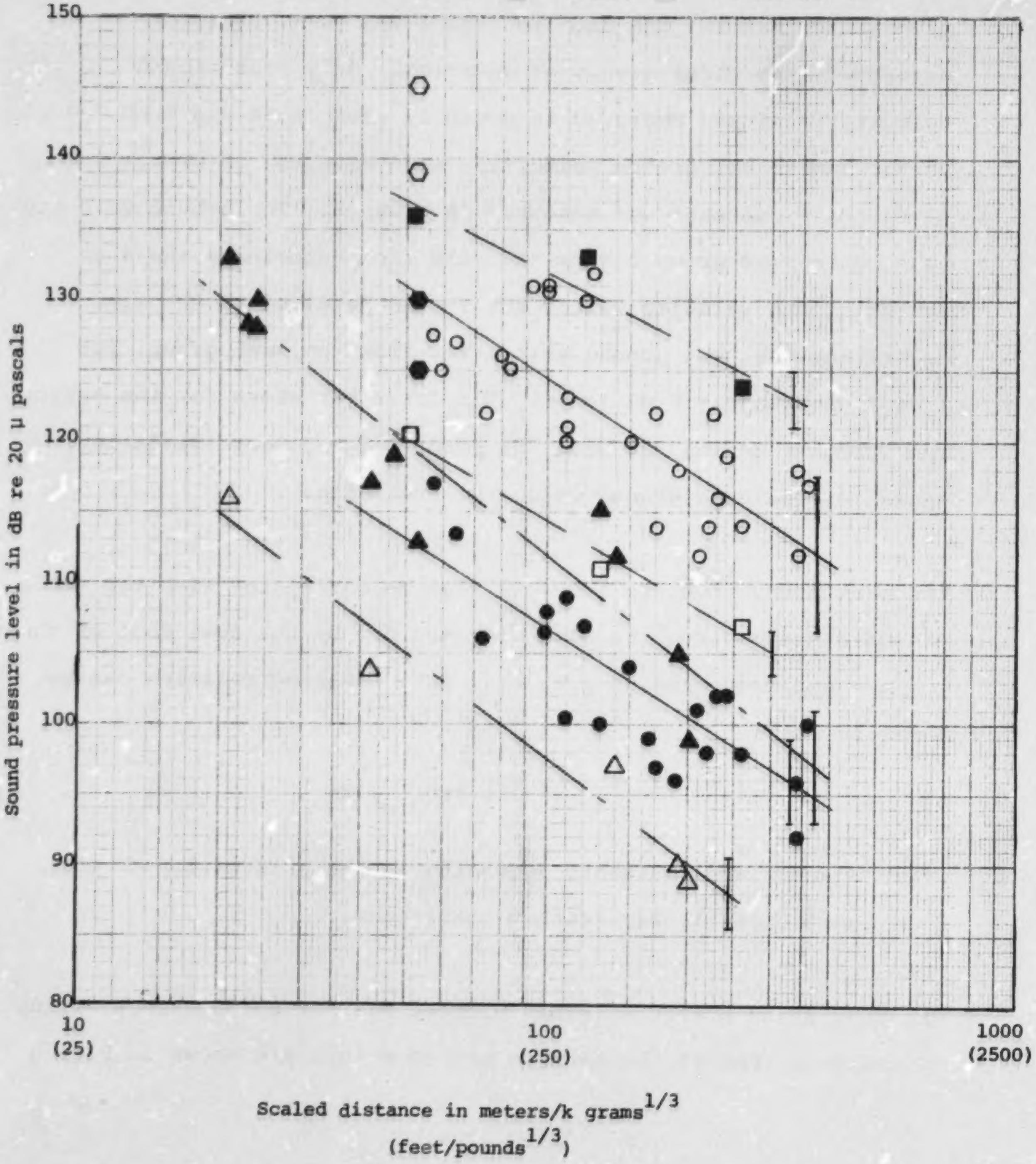
The peak sound pressure levels plotted against the distance divided by the cube root of the maximum charge weight are shown in Fig. 3.7-2.

Fig. 3.7-2. Sound Levels versus Scaled Distance

Downwind in front of face: ■ — Peaks, □ — 4-200 Hz SEL

Downwind behind face and
crosswind in front of face: ○ — Peaks, ● — 4-200 Hz SEL

Crosswind behind face: ▲ — Peaks, △ — 4-200 Hz SEL



These measurements (41 blasts) were made at seven limestone quarries, two silica sand quarries, and one open pit coal mine. To form a close-fitting straight line (linear regression) the peak levels were divided into three groups. The highest group consists of data taken downwind and in front of the face. These data show a decay with distance of slightly less than inverse square spreading (20 dB per decade of distance). The lowest group consists of data measured under no-wind or crosswind conditions behind the face of the blast. These data show slightly more than inverse square spreading due to access attenuation from the wind. The data falling in the middle measurements were made downwind and behind the face or a few points in front of the face and crosswind (or no-wind). These data are nearly exactly 20 dB decay per decade increase in distance. The 4 Hz to 200 Hz SEL measurements are also plotted in Fig. 3.7-2 for the same three groups and give the same decay rates with distance as the corresponding peak data. Four data points remain (two peak levels and two SEL measurements) that are excessively high. These measurements were made of blasts that had gas leaks and were initiated by primacord. The straight lines describing the three groups of SEL data have nearly the same slopes as the straight lines describing the corresponding peak levels, but they fall between 14 and 18 dB lower than the peak levels. The error bars drawn for the SEL values are smaller than those drawn for the peak values.

The C-weighted slow meter responses from all outdoor measurements made during this study and the 1975 IEQ study have also been correlated to the charge weight and distance by the same relationship used to correlate the peak and 4 to 200 Hz SEL. These results are shown in Fig. 3.7-3. These data give a more gradual decay with distance than do the peak and 4 to 200 Hz SEL. In fact, these data show less attenuation with distance than simple inverse square spreading would predict. This problem is probably due to the error in the slow meter response system in accurately detecting this type of impulse signal.

Similar correlations have been drawn for the 4 to 200 Hz slow meter response and the C-weighted SEL. These data are presented in Fig. 3.7-4. The slow meter response for a 4 to 200 Hz filter also shows a decay rate with distance more gradual than would be predicted by inverse square spreading. The C-weighted SEL data displays exactly 20 dB per decade change in distance.

A number of conclusions can be drawn from the results of this study with respect to the magnitude of the air blast and ground vibration from a blast event:

(1) Neighbors downwind from the blast will experience levels between 10 dB and 15 dB higher than neighbors crosswind from the blast (or those under no-wind conditions).

(2) Neighbors in front of the face of the blast will experience levels between 5 dB and 10 dB higher than those behind the face of the blast (or in the case of a lift shot).

(3) The blasting methodology is very important in controlling

Fig. 3.7-3. Sound Levels versus Scaled Distance for C-Weighted Slow Response

Downwind in front of face: ○

Downwind behind face and crosswind in front of face: ▲

Crosswind behind face: ⬡

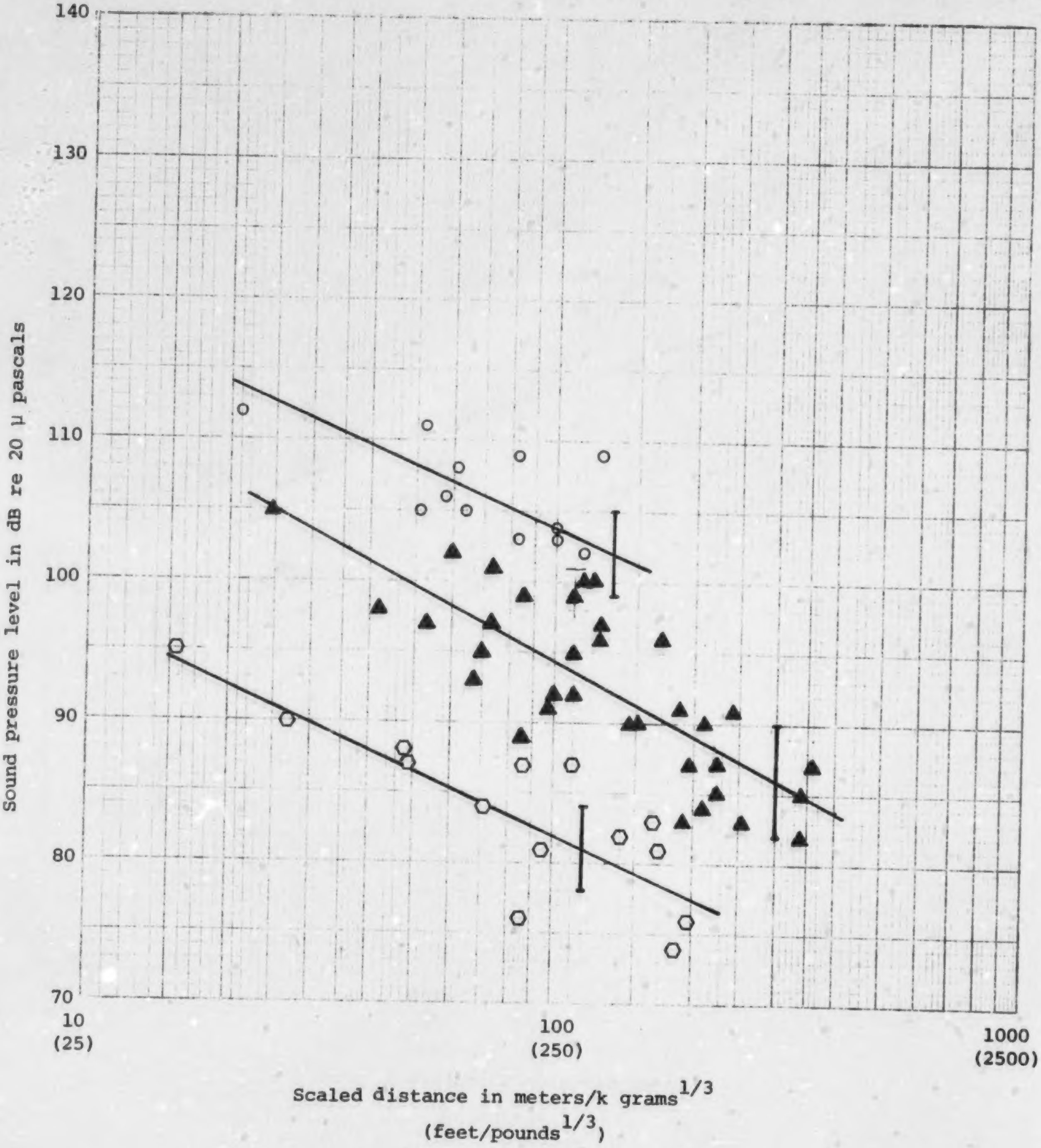
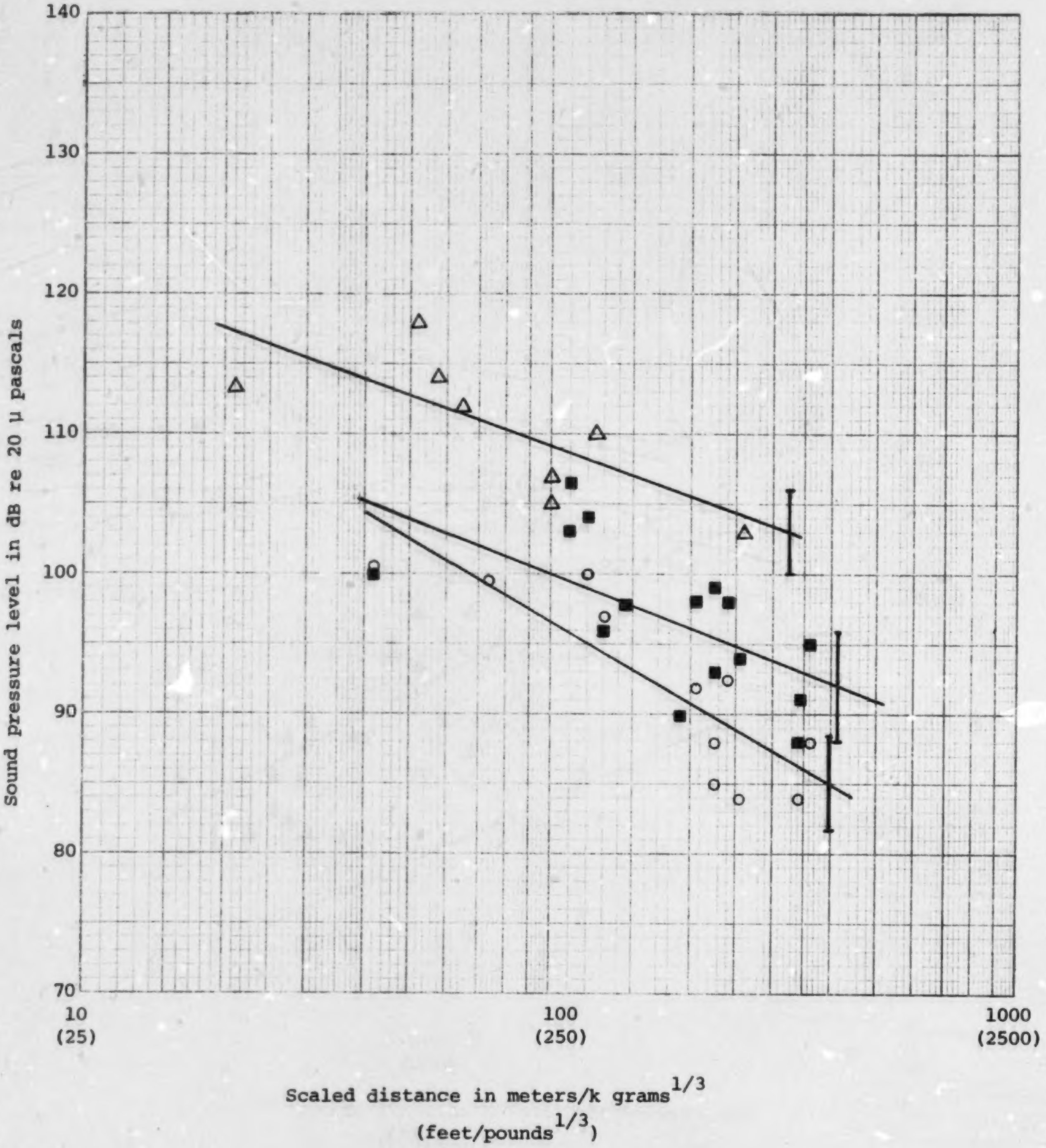


Fig. 3.7-4. Sound Levels versus Scaled Distance

Downwind in front of face: △ — 4-200 Hz Slow

Downwind behind face and
crosswind in front of face: ■ — 4-200 Hz Slow, ○ — C-Weighted SEL



the blast noise and vibration emitted to the neighbors.

(4) The 4 to 200 Hz SEL or CSEL can be predicted from the distance, explosive charge weight per delay, wind direction, and orientation to the face at least as well as from the peak-over-pressure measure.

(5) Although data from every quarry confirm the general principle that log velocity level (ground vibration) is inversely proportional to log distance per square root of charge, each quarry may have a different slope and intercept to the line describing this propagation rate.

(6) Quarries within a few kilometers of each other may have exactly the same propagation rate for the ground wave.

(7) The 4 to 200 Hz VEL of the vector sum of the ground velocity level can be predicted at least as well as the peak ground velocity level from the distance and the explosive charge weight per delay, as well as from previous knowledge of the quarry.

3.8 General Observations

All peak ground velocity data measured outside during this study and the 1975 study were well below the damage criterion of -26 dB re 1 m/sec (2 inches/second). All but one peak air blast over pressure level measured during these two studies were also below the lowest damage criterion of 140 dB re 20 μ pascals (0.028 psi).[2] The one blast over pessure that was in excess of 140 dB was measured on the property of an open pit coal mine. Therefore, all blasts measured may be considered to be in the annoyance range (or lower) but not a damage risk to dwellings. All basts were both heard and felt by monitoring personnel, but some low-level blasts passed by unnoticed by the residents, who were unaware of the exact time of the blast.

4.0 RECOMMENDATIONS

Section 3.4 discusses a wide variety of noise and vibration descriptors that may be utilized to determine the transfer function of a quarry blast from measurements performed outside a typical dwelling to the blast noise and vibration expected inside the dwelling. After completion of the field measurements, a further study was made of descriptors that would correlate best with the blast noise and vibration produced by a quarry blast. Until this time, it has been common practice to measure the peak ground velocity in the three mutually perpendicular axes (or peak vector sum of the three axes) and the peak-over-pressure of the air blast during a quarry blast event. The Bureau of Mines[1] has related the peak air blast over pressure and the peak ground velocity to the maximum charge weight per delay in the blast. The data obtained on the current EPA study fit the Bureau of Mines scaling models very well. It was also discovered that the velocity vector sum 4 to 200 Hz VEL fitted the Bureau of Mines scaling methodology for ground vibration better than did the peak ground velocity. The CSEL or 4 to 200 Hz SEL fit the Bureau of Mines scaling model better than did the peak-over-pressure of the air blast. Other descriptors such as C-weight slow meter response, and 4 to 200 Hz slow meter response were also compared to the Bureau of Mines scaling model and found to be somewhat less accurate for both the ground vibration and the air blast. Thus, in selecting descriptors for determining the transfer function of a typical dwelling, one should also be aware of some of the limitations of relating the measured descriptors to the blast event itself.

4.1 Suggestions for Monitoring Blasting Events with Respect to Annoyance of Residents in Typical Dwellings

It is not at all clear whether the peak or the total energy density (SEL or VEL) contained in the blast noise and dwelling vibration is the more annoying to the residents within the dwelling. This subject was not addressed in the current study. Wherever possible, one measurement descriptor was suggested in Section 3.4 to permit one to predict the peak vibration, or noise response of the structure, and another descriptor to predict the energy density (VEL or SEL) within the structure. For air blast measurements, CSEL or, as a second choice, C-weight type 1 slow response is recommended. For ground-borne vibration measurements, 4 to 200 Hz vector sum VEL or, as a second choice, vertical or lateral 4 to 200 Hz type 1 slow response is recommended.

4.2 Future Research Needed to Formulate a Blast Noise and Vibration Regulation

It can be seen from the results of this very limited study that much more is now known than previously about the response of typical dwellings to the blast noise and vibration associated with stone quarry blasting activities. However, this is only a very small part of the overall blast noise and vibration problems that affect residents exposed to large blast events.

4.2.1 Psychological Studies for Long Duration Impulses

Probably the least understood area in the blast noise and vibration phenomenon is the response of residents in dwellings subjected to the blasting activities of a nearby quarry or open pit coal mine during blasting events. It has been stated correctly that the peak vibration in a dwelling caused by the hard slamming of a door may equal or exceed the peak velocity (measured in the floor of a dwelling) resulting from blasting activity at a nearby quarry or open pit mine. A door slamming event is over within approximately 0.01 seconds. A typical quarry blast accompanied by a strong air blast continuously shakes a dwelling for a period of 5 seconds or more. But since the blast event causes the dwelling to shake 500 times longer than the slamming of a door, a measurement of peak floor velocity alone would probably prove insufficient in attempting to correlate these two events with human annoyance. The current study also indicated that a blast containing a broad frequency range both in the ground-borne and airborne waves can result in strong sinusoidal motion of the floor inside a dwelling.

The question must be raised as to whether the annoyance is the same for sinusoidal motion versus broadband excitation having the same peak value or SEL or VEL value.

Another area of interest is the importance of the structure-borne vibration sensed by a resident versus the inside airborne noise generated by the shaking of the structure. What are the relative effects of these various blast-generated stimuli in startling and annoying residents?

As a tentative criterion, CHABA Working Group 69 has proposed[9] a frequency-weighted peak acceleration (5.6 Hz single-pole low-pass filter) measurement of ground vibration in the three planes. Above 10 Hz, the CHABA methodology gives a constant conversion factor of one m/s^2 = 1.1 in/s velocity. Below 10 Hz, the CHABA method is less sensitive than velocity.

4.2.2 Effects on Various Blasting Configurations

The Bureau of Mines, quarry associations, and independent quarry operators have experimented over the years with a variety of blasting techniques to minimize air blast and ground-borne vibration. Most of this work was aimed at minimizing structural damage to dwellings and other nearby buildings during blasting. Peak ground velocity and peak-over-pressure were found to be good descriptors of structural damage. However, the blast noise and vibration levels which constitute an annoyance problem are probably of one order of magnitude below the levels which cause structural damage. Therefore, relating peak-over-pressure and peak ground velocity to the maximum charge weight per delay may not provide the best measure of annoyance to residents.

The rock and soil conditions surrounding a quarry operation determine the rate at which the ground vibration decays with distance. After this decay rate has been determined for a specific quarry, the scaling rules suggested by the Bureau of Mines can be applied. Sound propagation of the blast wave is not dependent upon the ground construction but is highly dependent upon the weather conditions immediately above and around the blasting operation. The blast propagation is most intense in front of the face (assuming it is a well controlled blast and no excess gas escapes either through the face or through "rifling", which is blowing the stemming out of the blast hole). More work needs to be done to determine the role of direction as a function of frequency of the sound propagation from the face being blasted. The results of the current study suggest that wind directions play a more significant role in the sound propagation of blast noise from the quarry than any other weather factor. This is a tentative conclusion that needs much further exploration.

All blasts monitored in homes during this study were well controlled to ensure that no "rifling" or "blowouts" occurred. Quarries in metropolitan areas are forced to carefully control their blasts to minimize complaints and avoid law suits. However, one quarry and a few open pit coal mine blasts that were monitored were far from any residents and therefore not subject to controlled blasting techniques. Hole blowouts were noticed for two such measurements, but were monitored only on the quarry or mine property since no home existed nearby.

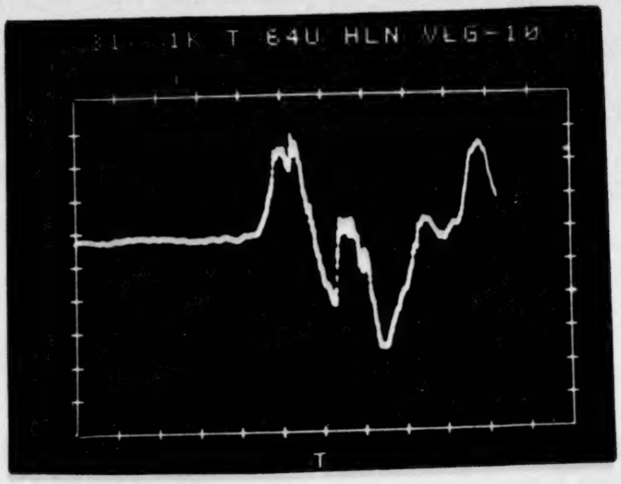


Fig. 4.2.2-1. Time history of blast prior to blowout (.2 sec time elapsed).

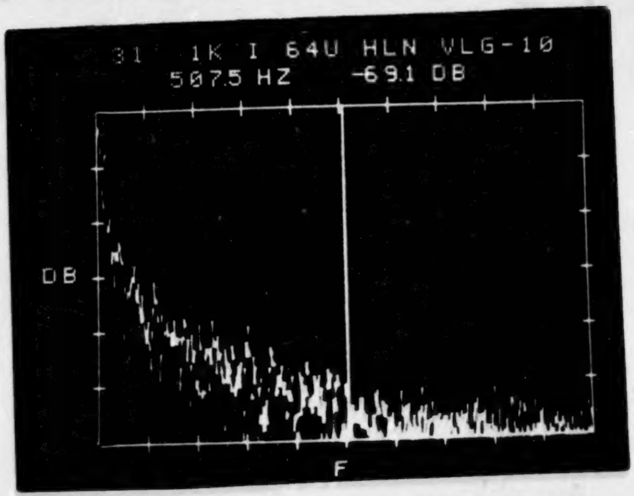


Fig. 4.2.2-2. Frequency spectrum of blast prior to hole blowout. Full scale 120 dB, frequency range 0 to 1000 Hz.

The importance of controlled blasting is shown in Figs. 4.2.2-1 through 4.2.2-4. Figure 4.2.2-1 is the time history of the first part of a stone quarry blast with its corresponding frequency spectrum ("F" is 0 to 1000 Hz, "dB" is 60 to 120 dB re 20 μ pascals) shown in Fig. 4.2.2-2. The rest of the time history of this same blast is shown in Fig. 4.2.2-3. The sharp rise time in this time history is caused by a hole blowout. The increased high-frequency energy caused by this blowout is shown in the corresponding frequency spectrum (from 0 to 1000 Hz) in Fig. 4.2.2-4. Comparison

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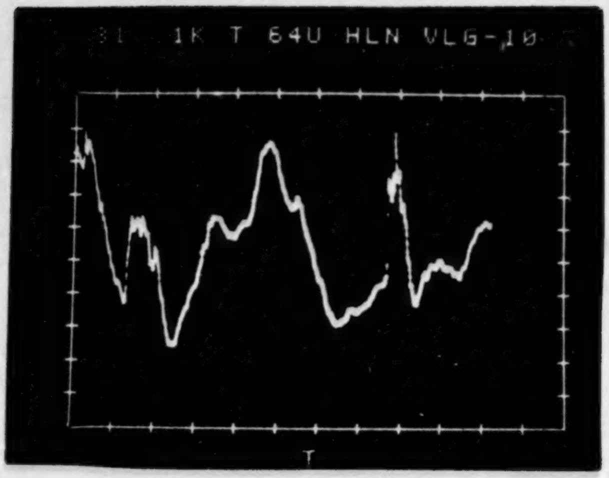

Fig. 4.2.2-3. Time history of blast, including hole blowout (0.2 seconds total time elapsed).

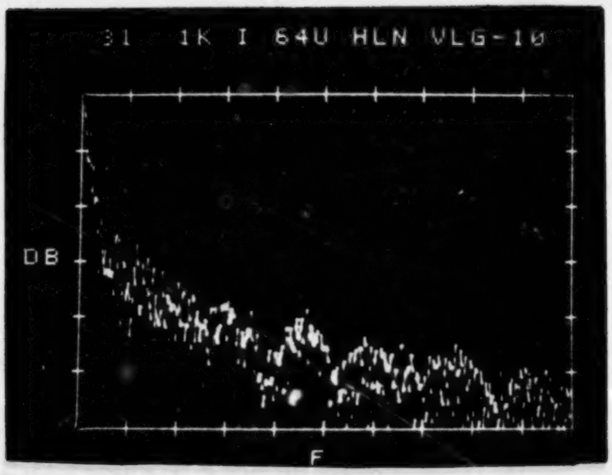

Fig. 4.2.2-4. Frequency spectrum of blast, including hole blowout. Full scale 120 dB, frequency range 0 to 1000 Hz.

of the two frequency spectra before and after the hole blowout suggests that the low-frequency (1 Hz) component, which is inaudible and has no effect on dwellings, is not affected by the blowout, but the higher frequencies (up to 1000 Hz), which shake dwellings and are audible, have increased from 5 dB to 10 dB. The instantaneous peak of this shot as determined by the time histories was not noticeably increased by the blowout. This suggests that the instantaneous peak value is not a good descriptor either for human annoyance or response of dwellings, especially for poorly confined blasts.

4.2.3 Economic Impact Versus Blast Noise and Vibration Control

Some stone quarries actively blasting in the vicinity of densely populated areas have demonstrated that it is economically feasible to utilize a blasting procedure that results in minimum complaints from nearby residents. Other quarries consistently produce complaints from their blasting activities. For this reason the entire problem area of cost-benefit for different quarry operation needs to be satisfied.

4.2.4 Determine the Transfer Function for a Broader Range of Living Quarters

The present study considered only typical single-family dwellings, with the exception of one instrumented structure, which was a much larger two-story office building. This concrete structure was found to be more responsive to blast noise and ground-borne vibration (see Section 3.6). Of particular concern are hospitals, dormitories, hotels, etc.

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APPENDIX A

DETAILS OF QUARRY BLAST NOISE STUDY

A.1 Measurement Objectives

The overall objective of this research program was to determine the transfer function of a typical home or dwelling for the airborne noise and ground-borne vibration observed outside and inside a typical dwelling during a quarry blast event. This current research program was a follow-on of the study conducted by Kamperman Associates Inc. in 1975 for the Illinois Institute of Environmental Quality on quarry blast noise.

At the outset of the current research program, a one-day meeting was held at Twin Cities Mining Research Center, Bureau of Mines, St. Paul, Minnesota on July 15, 1976. Representatives (18) from many organizations interested in the blast noise problem were present at this meeting. The one interested person who could not attend was Mr. David Siskind of the Bureau of Mines office at Twin Cities Mining Research Center.

The Bureau of Mines field group under David Siskind worked actively with Kamperman Associates Inc. on the blast noise study of 1975 for Illinois IEQ. A similar close relationship had been planned for the current research study. However, the tight schedule of the current study and the prior commitments by the Bureau of Mines for use of their field measuring instruments effectively ruled out any assistance from the Bureau. Throughout the 1975 study for Illinois IEQ, the Bureau of Mines under David Siskind made all the vibration measurements and a high percentage of the airborne blast measurements. Kamperman Associates Inc. and Illinois EPA made supplementary airborne blast measurements to obtain a better understanding of the blast noise phenomenon.

Since the Bureau of Mines was unable to assist in the current EPA blast noise research program, Kamperman Associates Inc. presented an alternative measurement system approach that would supply the basic data needed to fulfill the objectives of the study.

A.1.1 Blast Noise and Vibration Parameters to Be Measured and Studied

A consensus agreement was reached at the July 15, 1976 meeting on the different measurements to be tape-recorded for the EPA quarry blast noise study. Ground vibration measurements would be made immediately outside a dwelling of interest. The ground vibration would be measured with velocity-sensitive transducers attached to a concrete slab (not connected with the dwelling) to measure vibration in the three mutually perpendicular axes: lateral (often referred to as radial), transverse, and vertical. The blast noise would be measured both outdoor and inside the dwelling of interest. Inside the dwelling, velocity measurements supplemented by some acceleration measurements would be made of the floor motion (plus some consideration for wall vibration).

Typically this would be a measurement in the middle of a room on either the first or second level (where the latter was possible). In addition, it was requested that the A-weighted sound level inside the dwelling be measured during a blast. All data was recorded on magnetic tape for analysis in the laboratory after each recorded event.

A.1.2 Frequency Range of Interest

At the Bureau of Mines planning meeting of July 15, 1976, it was concluded that the frequency range of interest for measuring ground-borne vibration from quarry blasts could be adequately covered with a system responding from 5 to approximately 200 Hz. This frequency range would adequately cover the ground excitation from a quarry blast and include the structural resonances of interest in a typical dwelling.

The results of the study done for IEQ in 1975 revealed that the acoustic signal from the air blast had its peak energy at approximately 1 Hz. The outcome of the planning meeting at the Bureau of Mines suggested that the strong 1 Hz acoustic component should be tape-recorded even though the information of primary interest would probably be the higher frequencies that coincided with the structural resonances in the dwelling. The ISO document[7] on human response to vibration suggests that the primary frequency range of interest is from 1 to 80 Hz. The sound-level spectrum of principal importance inside a dwelling during a blast was the

C-weighted sound level supplemented by A-weighted sound-level recordings also obtained inside the dwelling. Various outdoor blast noise descriptors were to be explored to determine the best transfer function from the outdoor blast noise to the indoor blast noise and resultant vibration.

A.1.3 Dynamic Signal Range of Interest

The blast measurements for the 1975 IEQ study showed that the maximum ground velocity inside or outside a dwelling was approximately .025 meters per second or 1 inch per second (0 to peak). For the current EPA study, it was assumed that the ground vibration levels would be somewhat less than the vibration levels observed during the IEQ study due to the increased distance between the quarry blast and the monitoring location. A dynamic range for the velocity measurement was selected to encompass 0.00003 to 0.03 meters per second. The indoor acceleration dynamic range was set for 0.001 to 1 g. The indoor and outdoor sound pressure measurements were set to cover the range from 70 to 130 dB re 20 μ pascals. The A-weighted indoor sound-level meter was set to record the A-weighted sound level from 50 to 90 dB.

A.1.4 Selection of Measuring Transducers

Velocity-sensitive transducers were chosen to measure the vibration associated with each recorded quarry blast. Velocity-sensitive transducers have no particular advantage over acceleration-sensitive transducers. Velocity pickups have a high sensitivity and a low output impedance and thus relatively long signal cables can be utilized between the vibration transducer and the tape recorder without the need of a special preamplifier at the transducer. Velocity transducers utilize a moving coil operating above its resonant frequency. The piezoelectric accelerometer utilizes a ceramic and internally attached mass that produces an output signal proportional to acceleration below the resonant frequency of the accelerometer. Velocity transducers are relatively bulky and can only be utilized for measuring motion in one plane (without re-adjusting the coil suspension system). On the other hand, accelerometers are relatively small and lightweight and can be mounted to measure acceleration in any plane perpendicular to the base of the accelerometer.

The velocity transducers utilized for the current EPA project had a natural resonant frequency of 4.5 Hz. They were Geo Space model HS-1. A 470 ohm resistor was applied directly across the output terminals of the velocity transducer to critically damp the resonance frequency at 4.5 Hz. This provided an effective output impedance of approximately 150 ohms for each of the velocity transducers. Seven of these velocity transducers were used on the project. All the velocity transducers had the same sensitivity of 23 dB (± 0.25 dB) re 1 volt at 1 meter per second.

It has been demonstrated that quarry blasts produce ground vibration in the frequency range above 5 Hz. Experience has shown that structural resonances in typical dwellings are also in the frequency range above 5 Hz. However, the air blast produced by a quarry can have a very strong component around 1 Hz and thus it was determined that some measurements of floor vibration in typical dwellings should be made to observe the influence of the 1 Hz-dominated air blast on the response of the dwelling. A GenRad type 1560-P54 accelerometer was utilized to record the motion of the floor vibration down to 0.5 Hz. The output of the accelerometer was fed directly into a GenRad type 1933 microphone preamplifier that had been modified to permit the extended low frequency response.

To faithfully record the peak value of the 1 Hz component associated with the blast noise, it was important to have a microphone system with a frequency response extending approximately one decade below the lowest frequency of interest. The Bruel & Kjaer type 2631 microphone carrier system equipped with a type 4145 condenser microphone was utilized to measure the blast noise immediately outside and inside the particular dwelling of interest. The two low-frequency carrier systems were loaned to Kamperman Associates Inc. for the EPA blast noise measurement program. One unit was supplied by Dr. Paul Schomer (USA-CERL-EV, Champaign, Illinois), and the other unit by LTC. Daniel Johnson (AMRL/BBA-WPAFB, Dayton, Ohio). GenRad type 1971 ceramic microphones were also utilized to supplement the Bruel & Kjaer carrier microphone system. The ceramic microphones were selected to have a good low-frequency response of not more than 3 dB down at 0.5 Hz when connected to the GenRad type 1933 microphone preamplifier.

The photograph in Fig. A.1.4-1 illustrates most of the noise and vibration transducers utilized in this study. The right half of the photograph contains the sound-measuring instrumentation plus calibrators and windscreens. The left half of the photograph illustrates the vibration-measuring transducers and a laboratory vibration calibrator in the background. The small box located in the lower left corner of the photograph contains the battery power supply for the GenRad 1933 preamplifier shown between the battery box and the accelerometer. A similar power supply and preamp was used with the special low-frequency ceramic microphones. Six velocity transducers are shown in Fig. A.1.4-1. The velocity

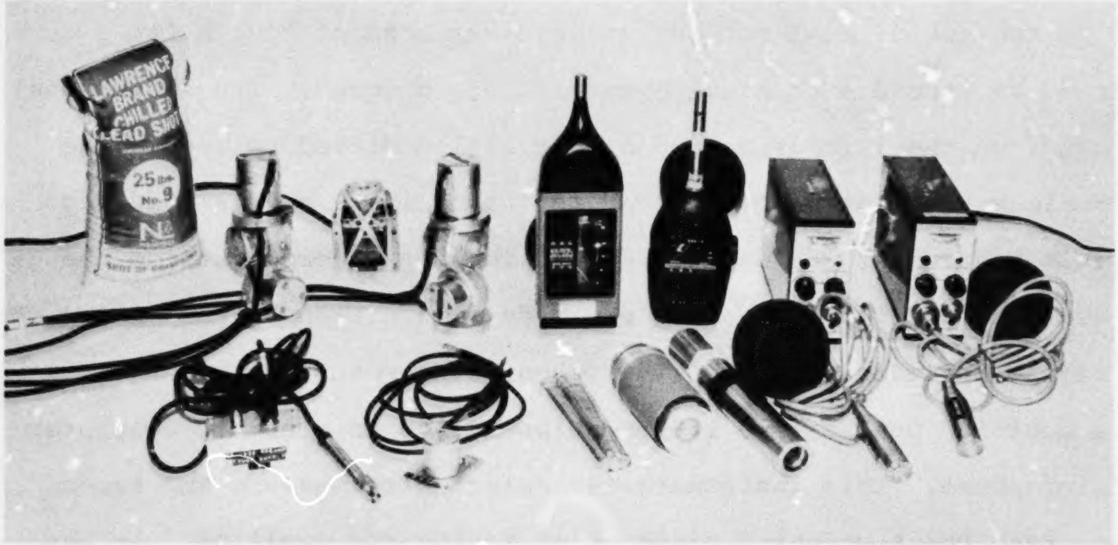


Fig. A.1.4-1 Blast noise and vibration-measurement transducers.

transducers are mounted in two seismic cages. They are mounted to measure lateral (radial), transverse, and vertical floor motion. The seismic cage configuration was always utilized for the outdoor ground velocity measurements. This configuration was also utilized for indoor floor measurements plus supplemental measurements with velocity pickups on the accelerometer. In a few rare instances the floors inside a monitored dwelling contained wall-to-wall carpeting, which made secure attachment of the vibration pickup to the floor virtually impossible. In these instances, individual transducers were placed on the carpet and a heavy mass, such as the 25-pound bag of lead shot shown in the upper left corner of Fig. A.1.4-1, was placed on top of the transducer to insure that each transducer followed the motion of the floor and was not isolated by the resiliency of the carpet under the transducer.

The two sound-level meters in the background of Fig. A.1.4-1 were used to record each blast event in this program. The sound-level meter on the left is a GenRad type 1981 modified to record the maximum C-weighted sound level on its built-in digital display. This instrument was used to record the blast noise outside the dwelling. This measurement was made in addition to the microphone signal recorded on tape. The sound-level meter on the right is a modified GenRad type 1565B equipped with an electret condenser microphone. This instrument was selected to measure and record on tape the A-weighted blast noise inside the dwelling. It was anticipated that the 1 Hz blast component would be 40 to 60 dB above the A-weighted sound level. For this reason it was essential to select an instrument that performed the A-weighting function before any amplification, to avoid potential overload of the A-weighted recording due to excessive low-frequency energy.

A.1.5 Selection of Data-Recording Instruments

To meet the measurement objectives of the EPA quarry blast study, it would have been ideal to use a tape recorder with a minimum of nine data channels covering a frequency range from 0.1 Hz to 10,000 Hz and possessing a very wide dynamic range. The recording problem was solved by leasing a new Hewlett Packard type 3968A eight-channel FM tape recorder. All of the sound and vibration measurements could be accommodated with a recorder having a bandwidth of 0.1 to 1,000 Hz, except the A-weighted sound level measured inside the dwelling. To solve this latter problem, the output signal from the A-weighted sound-level meter was fed directly into a portable cassette data recorder (Sony TC-152). The instruments used in the field (and in the laboratory) are shown in the photograph in Fig. A.1.5-1. The actual electrical hookup or connection between the various sound- and vibration-measuring transducers and the recording instruments is illustrated in block diagram form in Fig. A.1.5-2. The oscilloscope, a multimeter (DVM), and a 1 volt square wave generator are shown on the left side of Fig. A.1.5-1. These instruments were part of the field calibration and trouble-shooting equipment that were relied on heavily to avoid obtaining erroneous or useless recorded information.

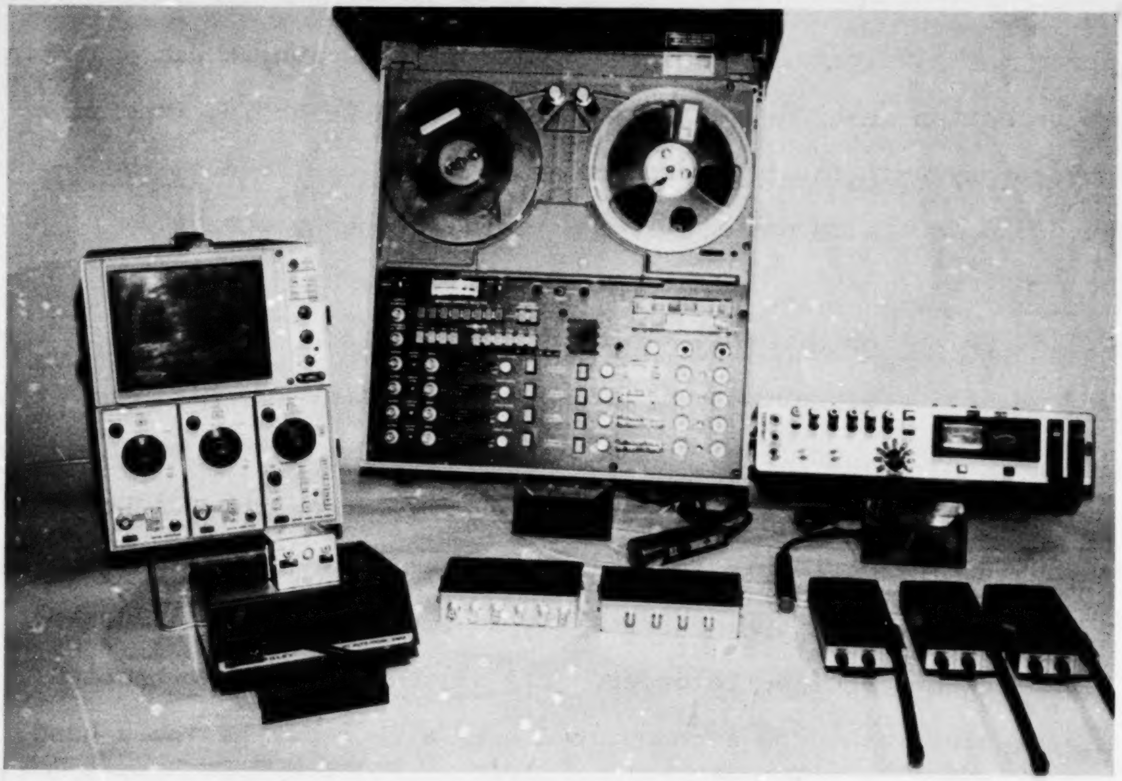


Fig. A.1.5-1 Blast noise and vibration-recording instruments.

The two magnetic tape recorders are shown in the background of Fig. A.1.5-1. The two small preamplifier units and the three transceivers in the foreground of the photograph are discussed in Section A.2.

A.1.6 Calibration of Instrumentation

The electrical calibration of all instrumentation was tested very extensively in the laboratory prior to the first quarry blast measurements to determine all the important features required to successfully record and analyze the noise and vibration phenomena.

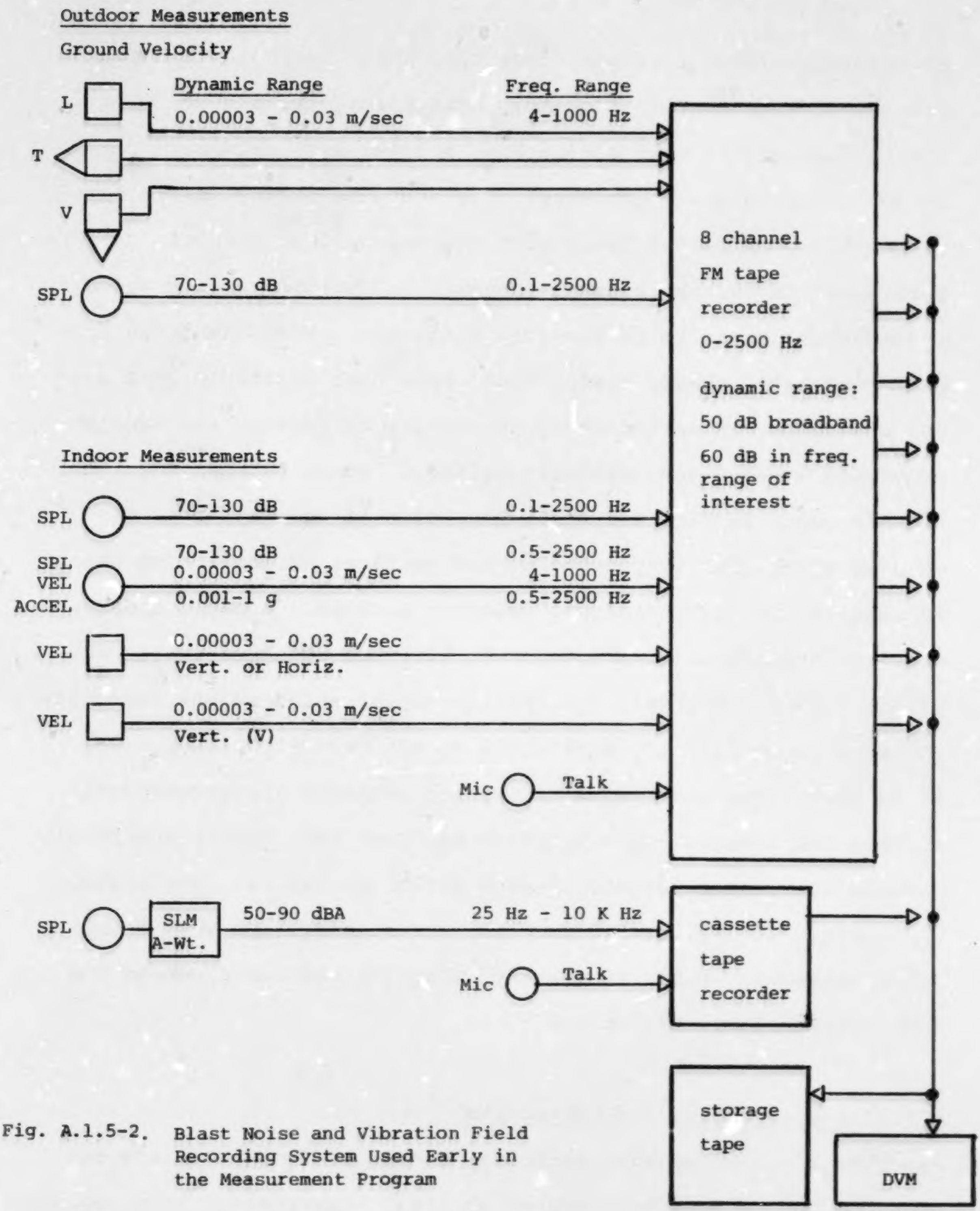

Outdoor Measurements
Ground Velocity
Dynamic Range
Freq. Range
L
0.00003 - 0.03 m/sec
4-1000 Hz
T
V
SPL
70-130 dB
0.1-2500 Hz
8 channel
FM tape
recorder
0-2500 Hz
dynamic range:
50 dB broadband
60 dB in freq.
range of
interest
Indoor Measurements
SPL
70-130 dB
0.1-2500 Hz
SPL
VEL
ACCEL
70-130 dB
0.00003 - 0.03 m/sec
0.001-1 g
0.5-2500 Hz
4-1000 Hz
0.5-2500 Hz
VEL
0.00003 - 0.03 m/sec
Vert. or Horiz.
VEL
0.00003 - 0.03 m/sec
Vert. (V)
Mic
Talk
SPL
SLM
A-Wt.
50-90 dBA
25 Hz - 10 K Hz
cassette
tape
recorder
Mic
Talk
storage
tape
DVM

Fig. A.1.5-2. Blast Noise and Vibration Field Recording System Used Early in the Measurement Program

The tests included frequency response, phase response, dynamic range as a function of frequency, gain stability, and dc drift. The transducers illustrated in Fig. A.1.4-1 were calibrated periodically in the laboratory. The sound-measuring instruments were calibrated in the field with the appropriate acoustic calibrators shown in the photograph. Dynamic calibration of the velocity transducers proved to be the most difficult. A medium-force electromagnetic shaker system would have been desirable, but was not available. A satisfactory substitute calibrator was made by modifying a heavy-duty magnetic solenoid, shown between the two seismic cages in Fig. A.1.4-1. The solenoid was supported by a large bench vise to provide either vertical or horizontal motion as required by the individual velocity pickups. A small accelerometer (with calibration traceable to NBS) was attached to the end of the velocity pickup. The voltage to the solenoid was carefully adjusted to provide 1 g excitation of the velocity pickup. The 60 Hz power line was used to drive the solenoid (electromagnetic shaker) and a narrow-band spectrum analyzer was used to accurately measure the output voltage of each pickup at 120 Hz. The pickup was excited at 1 g, at 120 Hz. The velocity pickups were found to be extremely stable in their sensitivity and all produced the same output signal within ± 0.25 dB.

A.1.7 Signal Cables and Connectors

Experience has shown that defective cables or connectors are the most common problems encountered in field measurements that require quality recordings of sound and vibration phenomena. To minimize such troublesome problems, all signal cables consisted of coaxial cable (RG-58C/U) meeting military specifications and BNC connectors and BNC hardware and adaptors. To check the signal cables in the field, a 1-volt square wave signal, first at 10 Hz and then at 100 Hz, was injected at the transducer end of the cable and monitored (at the other end of the cable) at the tape recorder with an oscilloscope to assure that the cable was performing as expected. The FM tape recorder electronics was also included in this electrical square wave test loop. This made it possible to quickly assess the frequency response and gain and proper functioning of the entire system short of the transducer. A square wave test signal was chosen to quickly check both the low and high frequency gain characteristics simultaneously for each transducer channel.

A.2 Blast Noise and Vibration Recording Systems

This section will discuss how the equipment described in the previous section was utilized on a typical field trip to measure a quarry blast. Mr. Greg Zak of Illinois EPA (IEPA) obtained blast noise recordings simultaneously with the recordings of Kamperman Associates Inc. The IEPA recordings were made much closer to the blast event (on the quarry property) in an attempt to gain additional data for scaling the blast noise as a function of distance and weather conditions. A brief discussion follows of the various instrumentation systems used in the 1975 Illinois

IEQ blast noise study. This section concludes with a description of the alterations made this year to the mobile system to improve the signal-to-noise ratio of the recorded signals.

A.2.1 The Mobile Recording System

The sound- and vibration-measuring transducers and recording instrumentation are shown in Figs. A.1.4-1 and A.1.5-1. The interconnection of these components is outlined in the block diagram of A.1.5-2. A small temporary bench placed upon the rear seat of a sedan supported the instrumentation shown in Fig. A.1.5-1. Time to respond to the announcement of a quarry blast was necessarily very short. From August 23 to the middle of October, 1976, personnel from Kamperman Associates Inc. were in daily contact with two or more of the five participating quarries in the Chicago area. The wind direction and the blasting schedule of a particular quarry, and the quarry's ability to locate a home to be instrumented downwind of the blast, determined whether or not one would be able to obtain an air blast measurement. It was agreed at the outset of the program that the quarry operators would be responsible for locating typical dwelling next to their quarry where measurements could be taken. To avoid any complications with neighbors, quarry operators agreed to restrict our measurements to the homes of quarry employees or close friends. A further requirement was that a member of the household must be at home at the time of the blast measurement. This combination of requirements made the measurement options very limited.

After receiving a go-ahead signal from a quarry that was preparing a blast and had located a home downwind of the blast, the team required approximately 10 minutes to connect up the instrumentation in an auto, an additional half-hour to arrive at the selected home, and 20 minutes more to set up recording instruments inside and outside the home. Sometimes the wind would change direction during the one-hour period before the blast, and the recorded blast would be crosswind rather than downwind of the blast.

The vibration transducers were attached to a concrete driveway or sidewalk outside the dwelling. Modelling clay was found adequate to securely attach the three component velocity gauges to the concrete. Several years ago, personnel from Kamperman Associates Inc. carried out carefully controlled experiments to determine the "best" method for measuring ground vibration. The best method is obtained by placing the vibration pickup securely on top of a 1-foot diameter previously poured concrete column that extends vertically 5 to 10 feet into the ground. The second-best choice is to bury the vibration pickups in the ground and firmly compact the soil after burial. However, this procedure has many drawbacks. It can prove very difficult to maintain proper orientation of the pickups while compacting the soil. Ground water and moisture are often a serious hazard. Digging a hole in the ground to bury vibration pickups can also be quite a chore, especially if the ground is frozen. For these reasons, the simplest choice is to place and secure the pickups onto a hard exposed level surface. This can and does produce almost as good results as could be obtained by placing the pickup on the specially poured and buried concrete column. The surface-mounted monitoring procedure is by far the easiest, and if one avoids utilizing concrete slabs that do not make firm contact with compacted earth, the measured results are usually within 1 or 2 dB or those made on the buried concrete column. A typical concrete roadway will show a slight resonance of around 60 Hz.

Inside the dwelling, the velocity pickups or accelerometer were generally mounted in the center of the floor, unless there was a major supporting beam immediately under the center. The floor surfaces consisted of a variety of constructions, including poured concrete slab on grade, poured concrete slab with a basement underneath, and, on the second floor of a large concrete block building, precast and prestressed concrete planks finished with poured concrete on top of them. One blast measurement was made on each of these constructions. All other measurements were made on a variety of wood frame constructions on the first or second floor of homes containing basements. The majority of the floor constructions consisted of standard oak flooring nailed to a wood subflooring. Some of the newer homes had plywood subflooring and a finished surface of hardwood, cemented vinyl tile, or cemented ceramic tile. After the transducers were secured to the floor surface, they were pulled on to assure that there was good contact between the transducer and the floor surface, and that the floor surface was securely attached to the subflooring. Occasionally wall-to-wall carpeting was encountered and required a different transducer-mounting procedure. The seismic cage containing the three velocity transducers was not used when carpeting was encountered. For the carpet situation, the transducers were removed from the seismic cage, placed directly on the carpet, and held in position with heavy weights, such as the 25-pound bag of lead shot shown in Fig. A.1.4-1.

The measurement of wall vibration as well as floor vibration during a blast event was considered early in the project. It was concluded that, with the limited resources available, the study should concentrate on the floor vibration. Although walls do vibrate from the ground wave and air blast, which may also rattle windows, dislocate bric-a-brac sitting on wall shelves, and transmit vibratory energy into the floor, it is the floor that ultimately shakes the occupants of the dwelling, and for this reason the vibration of the floor was considered the principal subject of interest for this study.

The outdoor sound-recording microphone was supported approximately 1-1/2 meters above the ground with a tripod, and located approximately 10 meters from the side of the dwelling. The microphone was positioned to receive the blast wave in much the same way that the dwelling would receive it, and at the same time to avoid blast noise reflection from the dwelling back to the microphone.

The indoor microphones were positioned on tripods and located in the rooms containing the floor vibration pickups. All microphones were covered with Bruel & Kjaer windscreens. The windscreens on the indoor microphones served only as physical protectors for the microphones.

Several redundant electrical field calibrations were performed before and after each blast event. The sound-measuring systems were checked with the appropriate acoustic calibrators. Field calibration of the vibration transducers could not conveniently be done. The operation of the vibration pickups was monitored on an oscilloscope before and after each blast by noting the signal from each pickup as a person walked across the floor inside the dwelling or on the concrete slab containing the outdoor vibration pickups outside the dwelling. Stable electrical calibration signals available from the data tape recorder plus the external portable square wave generator permitted accurate gain adjustment over a 26 dB range of 0.5 volts to 10 volts full-scale input voltage to the tape recorder.

Changing weather conditions have no known influence on the groundborne vibration from a quarry blast. However, local weather conditions, and particularly the wind, strongly influenced the magnitude of the air blast received at the dwellings studied. The wind direction was noted at the time of the blast and the wind velocity was measured with the small hand-held gauge shown in Fig. A.1.4-1 located just to the left of the acoustic calibrators in the foreground of the photograph. The cloud cover and air temperature were also recorded. The wind velocity at the edge of the quarry where the portable blast noise recorder was located always produced higher values because of the lack of obstructions such as existed in the residential area. The wind velocity measured at the edge of the quarry is reported with each blast event.

Reliable radio communication between the quarry blasting crew, the portable blast-noise-recording operator, and the operator of the mobile recording system at the instrumented dwelling proved to be essential. CB transceivers were initially used for this purpose in the 1975 Illinois IEQ blast noise study. However, it was soon discovered that all available frequency bands were so heavily utilized that it was sometimes difficult to coordinate the recording with the blast event. To circumvent the problem in the 1975 study, three transceivers operating at licensed commercial frequencies of around 150 megahertz were utilized. These hand-held transceivers are shown in the bottom right corner of Fig. A.1.5-1.

A.2.2 Portable Blast Noise Recorder

Mr. Greg Zak of the Illinois EPA assisted Kamperman Associates Inc. throughout the program. It was his objective to record the air blast simultaneously with the recordings being made by Kamperman

Associates Inc. (located at a more distant dwelling). The portable recorder was set up 100 to 500 meters from the actual blast. The portable recorder was always located within the property of the quarry.

A block diagram of the portable recording system is shown in Fig. A.2.2-1. A GenRad type 1971 ceramic microphone was connected to a GenRad type 1933 preamplifier. The output signal from the preamplifier was fed directly into the FM channel of a Nagra type SJ tape recorder. No gain controls or preamplifiers (except the microphone preamplifier) were used for the portable system. The low-frequency response of the microphone and preamp system was determined by very carefully inserting the microphone into a Bruel & Kjaer type 4220 pistonphone acoustic calibrator and observing the frequency spectrum that was produced when the calibrator was turned off and the pistonphone was allowed to coast to a halt. The same experiment was repeated utilizing the Bruel & Kjaer carrier microphone system with a known cutoff frequency of 0.1 Hz. By comparing the spectra captured on a real-time analyzer of the Bruel & Kjaer carrier system with the ceramic microphone and preamp system, the 3 dB down point could be determined for the ceramic microphone and preamp combination.

The measurement procedure utilized in the field was simple. The microphone and its associated preamplifier were supported approximately 1.5 meters above the ground with a tripod. An acoustic

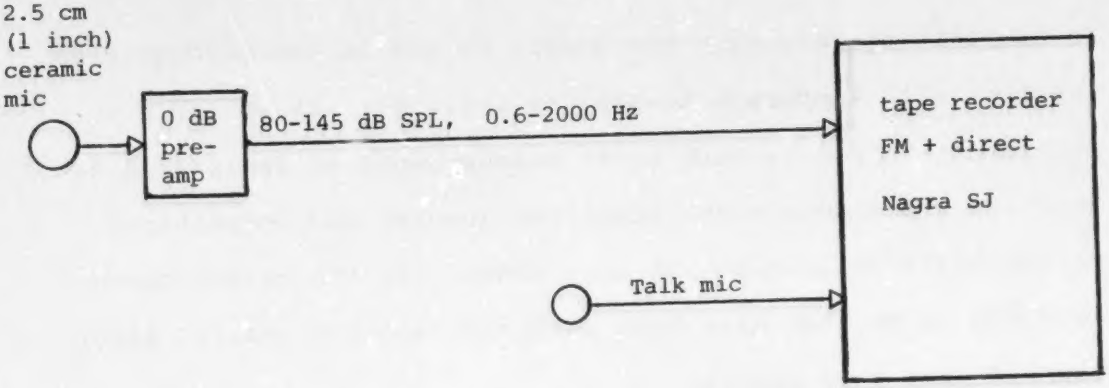

2.5 cm
(1 inch)
ceramic
mic
0 dB
pre-
amp
80-145 dB SPL, 0.6-2000 Hz
tape recorder
FM + direct
Nagra SJ
Talk mic

Fig. A.2.2-1. Portable Air Blast Recording System Used by Illinois EPA Personnel for the 1975 IEQ and 1976 EPA Quarry Blast Noise Study

calibration tone of 114 dB was applied to the microphone with a GenRad type 1562 calibrator. The calibration signal was recorded on the magnetic tape recorder prior to each blast.

In addition to recording the quarry blasts in the Chicago area together with Kamperman Associates Inc., Mr. Zak was able to supplement this data with blast measurements at two silica sand quarries and a down-state limestone quarry, and three blast measurements at an open pit coal mine. All the measurements recorded by Mr. Zak have been analyzed, and the results incorporated into this report.

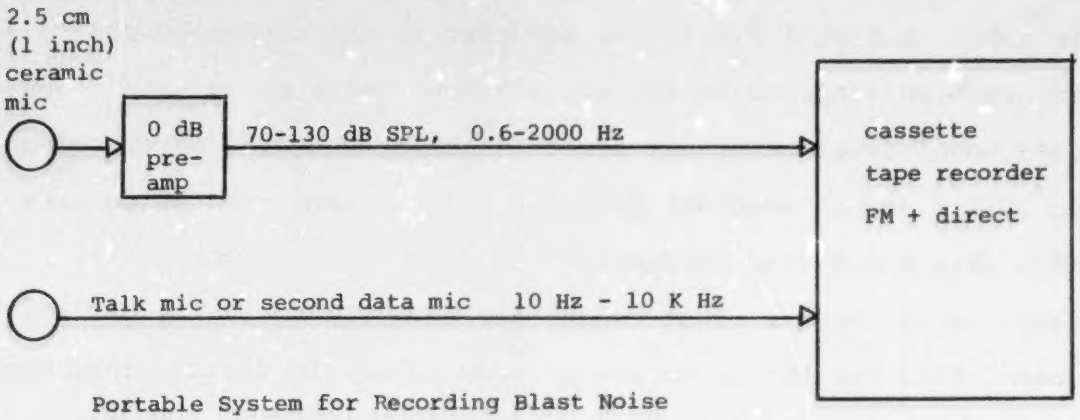
A.2.3 Recording Systems Used in Illinois 1975 IEQ Blast Noise Study

The most significant support for the IEQ blast noise study was provided by the Bureau of Mines at Twin Cities Mining Research Center under the direction of David Siskind. The Bureau of Mines provided the IEQ blast noise study with a van containing noise- and vibration-measuring and recording instrumentation plus staff to operate the equipment. A description of their instrumentation will be published in the spring of 1977.[11] Greg Zak of the Illinois EPA office in Springfield provided support to this EPA blast noise study similar to that he gave in 1975 to the Illinois IEQ study. The instrumentation system used by Greg Zak for both programs is shown in Fig. A.2.2-1. Kamperman Associates Inc. utilized a blast-noise-measuring system similar to that used by IEPA in 1975. A simplified block diagram of the recording system is shown in Fig. A.2.3-1. In addition to the tape-recorded information obtained by the three groups, each group used a GenRad 1933 sound-level meter set for C-weighting and slow meter response to obtain direct readings during a blast. Kamperman Associates Inc. also used a modified GenRad 1981 to read the C-weighted slow response of the air blast events for both studies. The modified GenRad 1981 had the advantage of reading out in digital form the maximum level reached (C-weight, slow response) in each blast, which was preferable to depending on the observer's ability to read a fast moving meter at the time the blast wave passed.

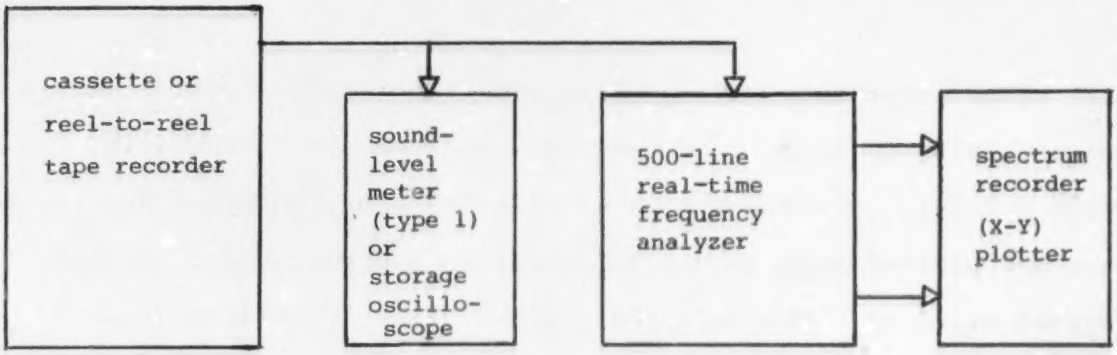
All blast recordings made by IEPA and Kamperman Associates Inc. on the 1975 IEQ study were analyzed with the system shown in Fig. A.2.3-1. The 500-line real-time frequency analyzer and the X-Y plotter were loaned to Kamperman Associates Inc. by the Bureau of Mines. The analyzer was a Nicolet Scientific Corp. model 500A. This is a time-compression-type analyzer with a Hanning window. The test results obtained from the analysis of the IEQ blast noise study have been reanalyzed with the 1976 data analysis system, designed for the EPA study, and are incorporated into the results of this report. The test results obtained by the Bureau of Mines during the IEQ blast noise study was recently published by the Bureau.[3] Data from their report is also incorporated into the summaries contained in this report.

A.2.4 Alterations to the 1976 Mobile Recording System

For the IEQ blast noise study of 1975, the Bureau of Mines made


2.5 cm
(1 inch)
ceramic
mic
0 dB
pre-
amp
70-130 dB SPL, 0.6-2000 Hz
cassette
tape recorder
FM + direct
Talk mic or second data mic 10 Hz - 10 K Hz

Portable System for Recording Blast Noise


cassette or
reel-to-reel
tape recorder
sound-
level
meter
(type 1)
or
storage
oscillo-
scope
500-line
real-time
frequency
analyzer
spectrum
recorder
(X-Y)
plotter

Laboratory Blast Noise Analysis System

Fig. A.2.3-1. Blast Noise Recording and Analysis System Used by Kamperman Associates Inc. for 1975 IEQ Study

all the vibration measurements. The results of their measurements are summarized in Ref. 3. These data show less of a decrease in ground vibration level with distance than was found on the quarries measured in the EPA study. The Bureau of Mines results from the IEQ study were the basis for establishing the vibration-measuring sensitivity requirements for the EPA study. It came as a surprise last fall to find that the quarries in the Chicago area produced less ground vibration. The ground vibration levels were lower than expected for a number of reasons. The charge weight per delay was, on the average, less last fall than that measured in 1975. Furthermore, the distance between the blast event and the instrumented dwelling was increased far more than had been anticipated (1000 meters) in order to separate the arrival time of the ground wave from the arrival of the airborne blast wave at the instrumented dwelling. To overcome these lower signal levels, 30 dB preamplifiers were quickly constructed and inserted in the signal leads from each velocity transducer. An additional preamplifier was constructed for the acceleration measurements that permitted a gain increase up to 40 dB in 10 dB steps.

The added preamplifiers are illustrated in Fig. A.2.4-1 in block diagram form and are shown in the foreground of the center of the photograph in Fig. A.1.5-1. In the early phase of the measurement program during the current study, two rooms were instrumented simultaneously in a dwelling. The sound level and the vertical velocity of the floor in the two rooms were recorded during the blast. It was believed that the vertical component in the floor would be the most significant motion during a blast. However, to prove this, it was decided that the three mutually perpendicular planes (lateral, transverse, and vertical) should be measured simultaneously. The limited number of available data-recording channels permitted the recording of sound and vibration in one room only during a blast event.

No additional technical problems were encountered during the field measurement phase of this program. The total number of recorded blast events was strictly dictated by the number of homes (18) located downwind of a quarry blast that were available for measurement.

A.3 Analysis of Recorded Blast Noise and Vibration

Immediately after the recording of each blast, the instrumentation was returned to the laboratory for analysis of the recorded signals. The storage oscilloscope was used in the field to check the condition of the recorded signals immediately after a blast if a second blast was to follow within an hour or two.

A.3.1 Data Analysis Systems

A wide variety of signal analyses was performed by the instrumentation shown in Fig. A.3.1-1. The data analysis methodology is described in the following subsections.

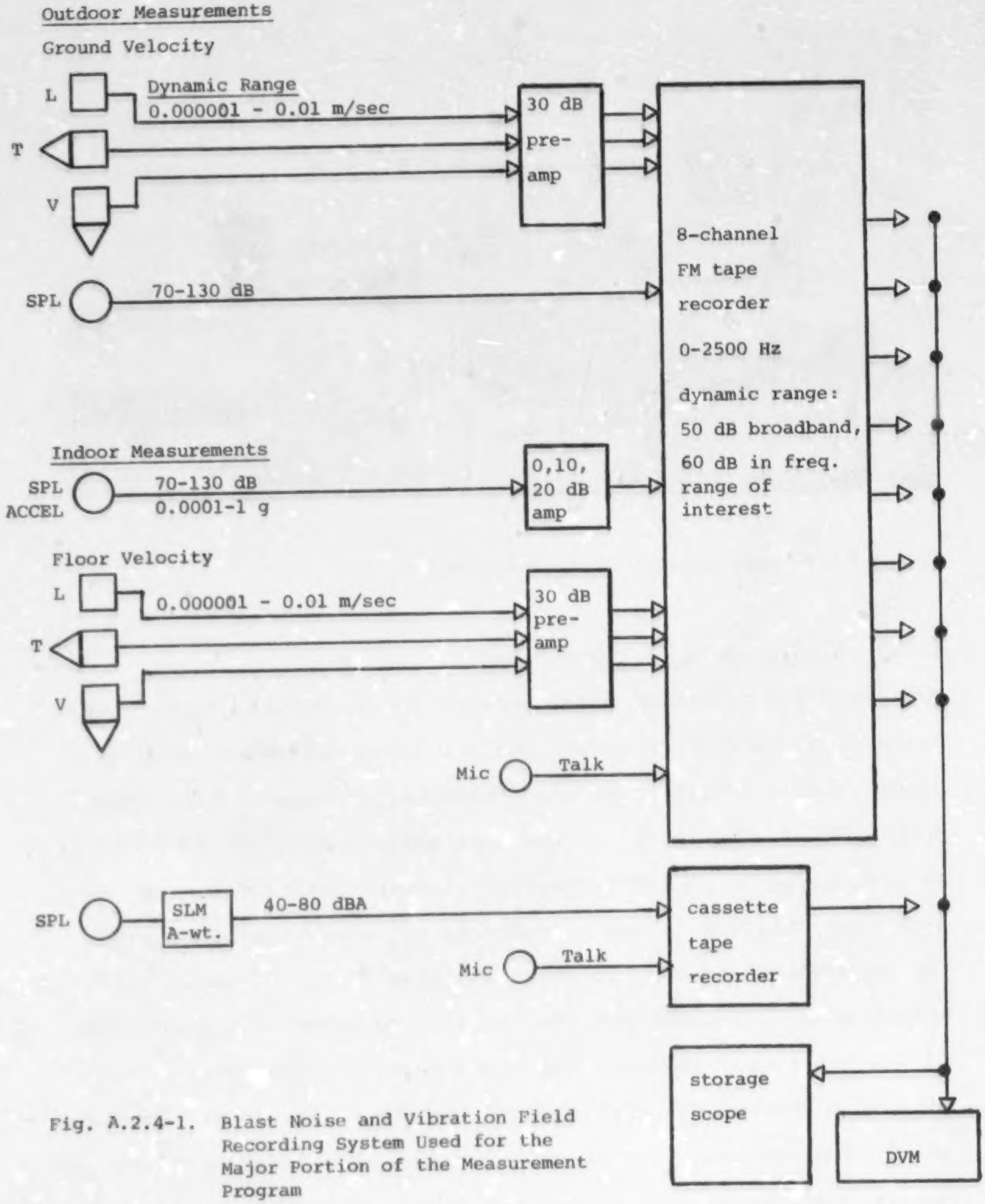

Outdoor Measurements
Ground Velocity
L
T
V
Dynamic Range
0.000001 - 0.01 m/sec
30 dB pre-amp
SPL
70-130 dB
8-channel FM tape recorder
0-2500 Hz
dynamic range:
50 dB broadband,
60 dB in freq. range of interest
Indoor Measurements
SPL
ACCEL
70-130 dB
0.0001-1 g
0,10, 20 dB amp
Floor Velocity
L
T
V
0.000001 - 0.01 m/sec
30 dB pre-amp
Mic
Talk
SPL
SLM A-wt.
40-80 dBA
cassette tape recorder
Mic
Talk
storage scope
DVM

Fig. A.2.4-1. Blast Noise and Vibration Field Recording System Used for the Major Portion of the Measurement Program

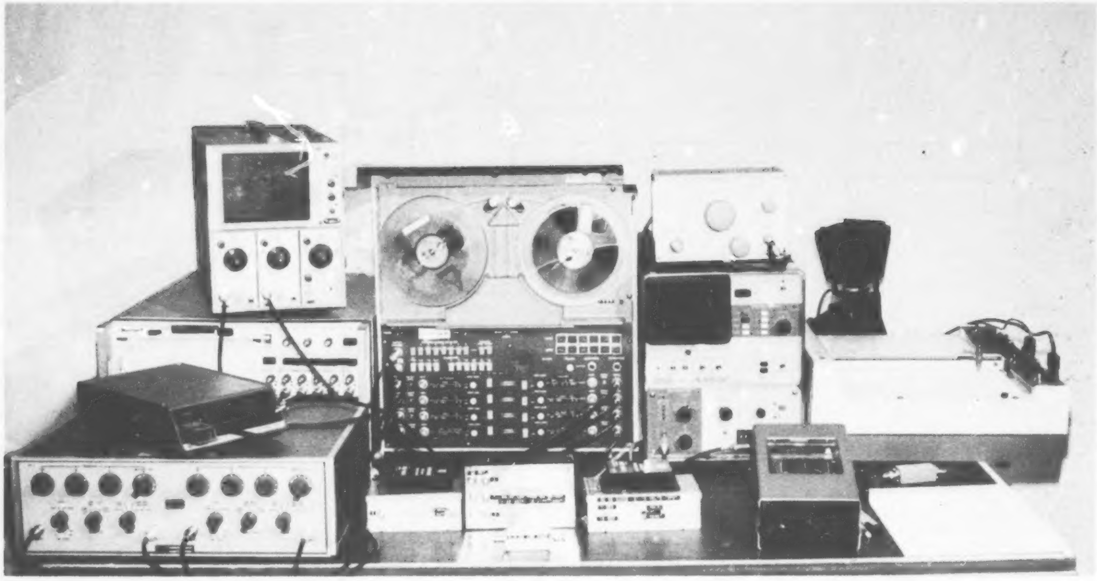


Fig. A.3.1-1 Data analysis instrumentation.

A.3.2 Time History of Blast Event

The sound and vibration data recorded on the Hewlett Packard type 3968A eight-channel tape recorder was first reproduced into an eight-channel oscillograph chart recorder (Honeywell Visicorder Model 1858). The setup for the time history analysis is shown in Fig. A.3.2-1. The FFT analyzer (Nicolet Scientific Corp. Model 440A) was utilized in the time domain to locate the blast event on the magnetic tape. The photosensitive strip charge is 0.2 meters wide (8 inches) and was normally operated at a chart speed of 0.1 meters per second. The blast event extended over a period of 5 to 8 seconds and thus some of the chart records are approximately 1 meter long. In order to present this information in this report, additional records were made with a more compressed time

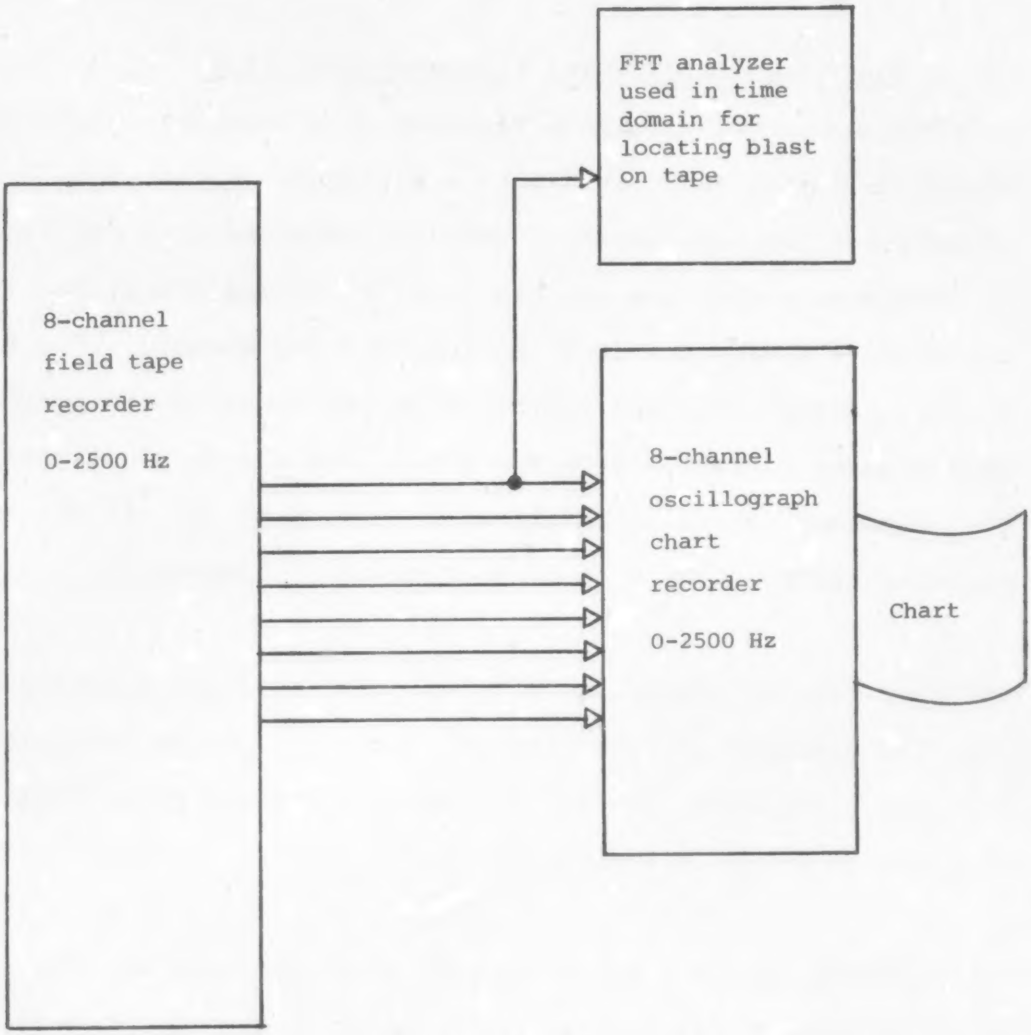

FFT analyzer used in time domain for locating blast on tape
8-channel field tape recorder
0-2500 Hz
8-channel oscillograph chart recorder
0-2500 Hz
Chart

Fig. A.3.2-1. Simultaneous Time History Analysis of Eight Noise and Vibration Signals Recorded During a Single Blast Event

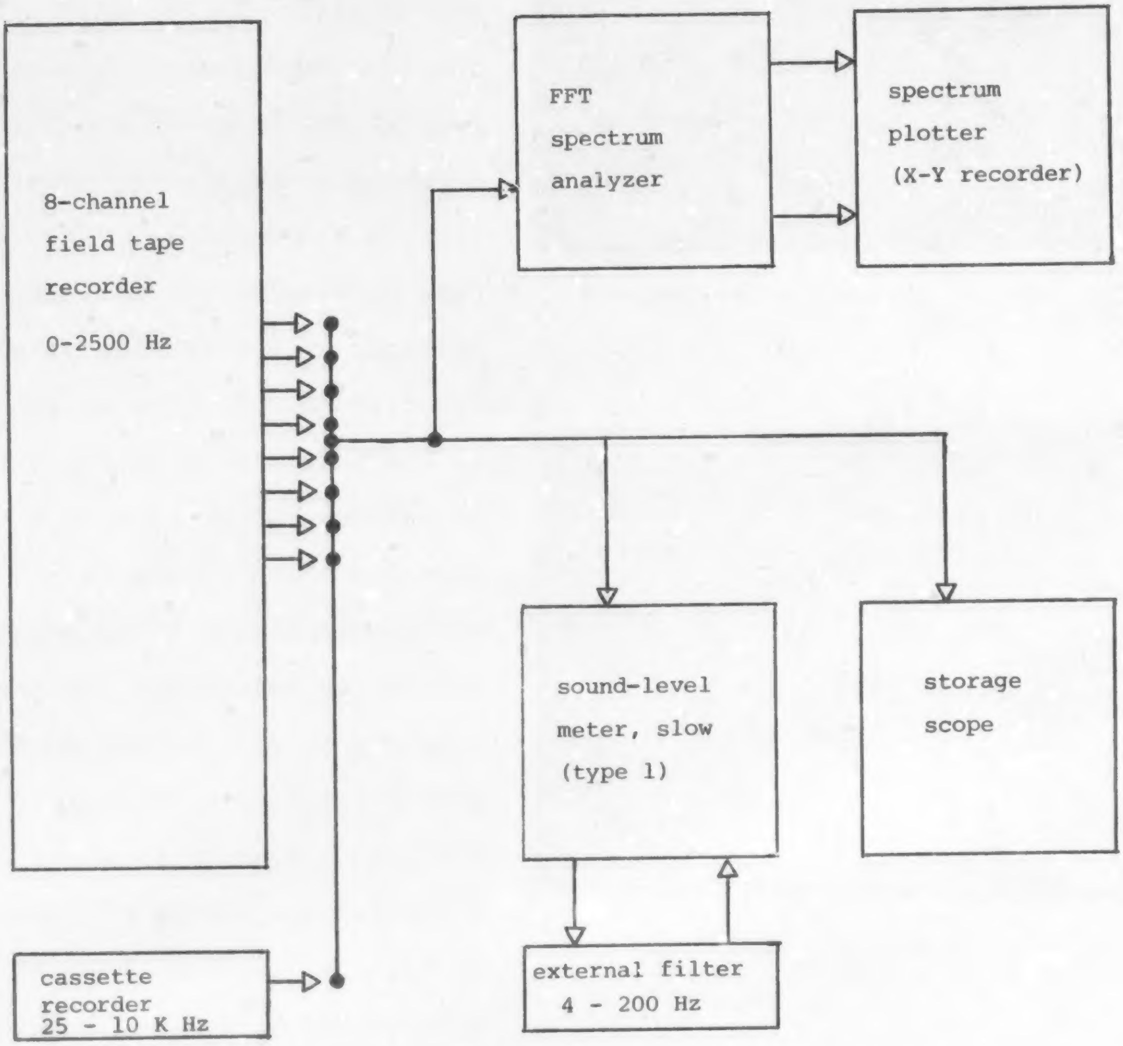
scale. The photo-sensitive record was then photographed and reduced 20% and placed in Appendix B. A detailed discussion of a typical record of blast noise and vibration amplitude is covered in Section A.4.

A.3.3 Spectrum Analysis and Frequency Weighting

A detailed spectrum analysis was made of a recorded noise and vibration signal associated with a particular blast event. The transducers located outside a dwelling recorded only one signal of interest; either the air blast or the ground vibration. The transducers inside the dwelling recorded two signals. The first signal was the noise and vibration in the house caused by the ground-borne vibration from the blast, and the second signal was the noise and vibration in the house caused by the air blast. A separate analysis was made of each of these signals.

The fast Fourier transform (FFT) spectrum analyzer provided a detailed spectrum of each signal. The spectrum was then plotted on graph paper with the aid of a Hewlett Packard type 7045A X-Y recorder as shown in Fig. A.3.3-1.

The spectrum analysis of an impulse or shock, such as that associated with blast noise, is best accomplished with a true FFT analyzer. It is also important that the impulse signal be stored unweighted in the time domain. A rectangular "window" should be used for analyzing impulses. This program is illustrated in Figs. A.3.3-2,



FFT
spectrum
analyzer
spectrum
plotter
(X-Y recorder)
8-channel
field tape
recorder
0-2500 Hz
sound-level
meter, slow
(type 1)
storage
scope
cassette
recorder
25 - 10 K Hz
external filter
4 - 200 Hz

Fig. A.3.3-1. Data Analysis System for Determining Blast Noise and Vibration Spectrum, Peak and Various Sound-Level Meter Descriptors

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A.3.3-3, and A.3.3-4. A 4-second-long air blast signal is shown in the photograph in Fig. A.3.3-2. This photograph was taken of the FFT display in the time domain for a typical blast. The same signal is then shown in the frequency domain in Figs. A.3.3-3 and A.3.3-4. The only difference between the settings on the FFT analyzer for Figs. A.3.3-3 and A.3.3-4 is the position of the weighting or "windowing" switch. The spectrum shown in Fig. A.3.3-3 was obtained with a rectangular window (no weighting) and the spectrum in A.3.3-4 was obtained with a Hanning weighting of the data displayed in Fig. A.3.3-2. The frequency range in Figs. A.3.3-3 and A.3.3-4 is 0 to 100 Hz full-scale with 10 Hz intervals marked along the top and bottom of the frequency (F) scale. The decibel

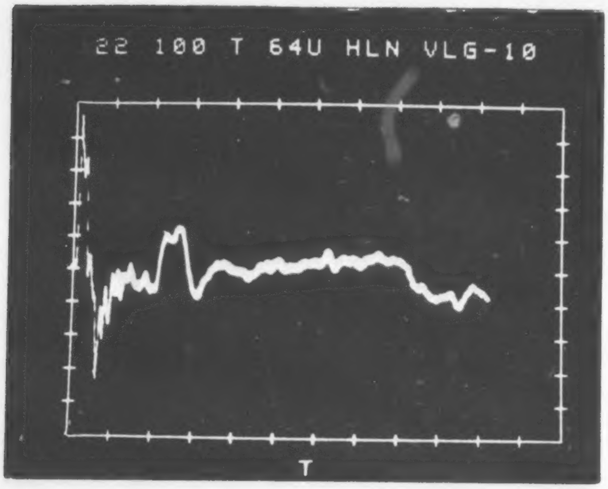

Fig. A.3.3-2 Amplitude—time history of an air blast.

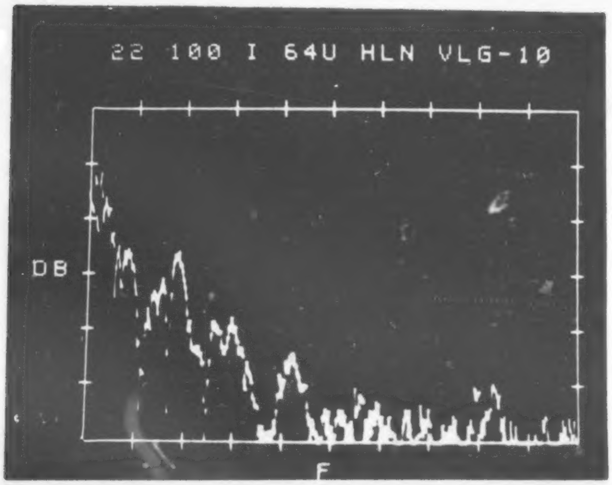

Fig. A.3.3-3 Air blast frequency spectrum with rectangular "window."

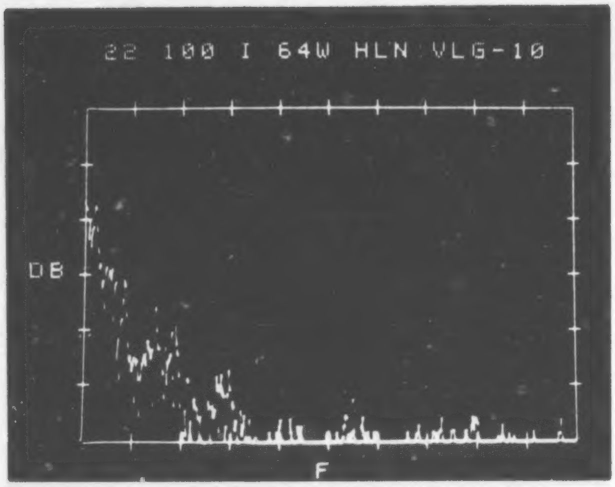

Fig. A.3.3-4 Air blast frequency spectrum with Hanning "window."

scale (DB) on the left is 60 dB full-scale and 10 dB per division. The difference in the spectra shown in Figs. A.3.3-3 and A.3.3-4 illustrates the magnitude of the error encountered in Fig. A.3.3-4 by utilizing the Hanning or cosine squared weighting on the blast signal shown in Fig. A.3.3-2. There is a peak in the spectrum at 18 Hz in Fig. A.3.3-3, which is suppressed about 15 dB in Fig. A.3.3-4. Many real-time spectrum analyzers which were on the market prior to the introduction of the FFT analyzer contain Hanning weighting only and thus are subject to the errors discussed here. This error with a Hanning window can be reduced to one dB or less if the entire signal of interest is positioned in the center half of the time storage (or window).

The detailed spectrum analysis of each quarry blast noise and vibration signal recorded was automatically plotted on a large sheet of graph paper.

Whenever the signal-to-noise ratio of the recorded signal was particularly poor, an additional spectrum analysis of the background noise just prior to the blast event was also analyzed and plotted to permit one to separate out the "wow" and "flutter" components of the tape recorder from the true noise and vibration signal of interest. Faithfully recording the entire frequency spectra of quarry blast events requires a data-recording and reproduction system with outstanding dynamic range. The eight-channel FM tape recorder had a 50 dB dynamic range over the total bandwidth from 0 to 2500 Hz when recording and reproducing at a tape speed of 19 cm/second (7.5 ips). In the primary frequency range of interst (0 to 200 Hz) the dynamic range of the tape recorder was 60 dB. This dynamic range was set by the fundamental frequency of the wow and flutter component (near 6 Hz). All harmonics of the wow and flutter component were more than 70 dB down. The tape recorder had a harmonic distortion level of less than 0.3% at full record level. The portable cassette data recorder shown in Fig. A.3.3-1 was utilized to record the A-weighted sound level inside a dwelling during a blast. The broadband dynamic range of this recorder was approximately 45 dB with a maximum harmonic distortion level of 1%.

Many different analyses were attempted utilizing the standard type 1 (precision) sound-level meter with different weighting networks or external filter networks. The adjustable high-pass, low-pass filter was a Kron-Hite model 3322. The roll-off characteristics outside the band pass for this filter is 24 dB per octave. The sound-level meter shown in the block diagram in

Fig. A.3.3-1 was a GenRad type 1933. This instrument was sometimes replaced by a GenRad type 1981 that had been modified for C-weighting. The modified instrument had the advantage of being able to capture the maximum signal level and display it continuously in digital form. The frequency spectra of all data for this study is available at EPA/ONAC. Comparisons of various descriptors are summarized in several tables contained in Section 3.4

A.3.4 Determination of the Noise and Vibration Energy (VEL) from a Blast Event

The system assembled for determining the energy density (VEL and SEL) using various filtering devices is shown in Fig. A.3.4-1. The oscilloscope and the FFT analyzer served primarily to locate the portion of the blast event that was to be analyzed (separating the indoor noise and vibration from the ground wave and the air wave produced by a quarry blast). The oscilloscope was used primarily to assure that the DC offset in the signal entering the squaring device was at or near 0 volts DC immediately prior to the arrival of the blast signal. The squaring and integrator was a DC pass system and thus it was most important to avoid any undesirable DC offset into the detector system, since this would lead to errors in the final answer. The squaring device was made up of analog computing modules. The integrator was a classical Miller integrator with a selectable time constant of 1 second or 10 seconds. The output of the integrator was fed directly to a

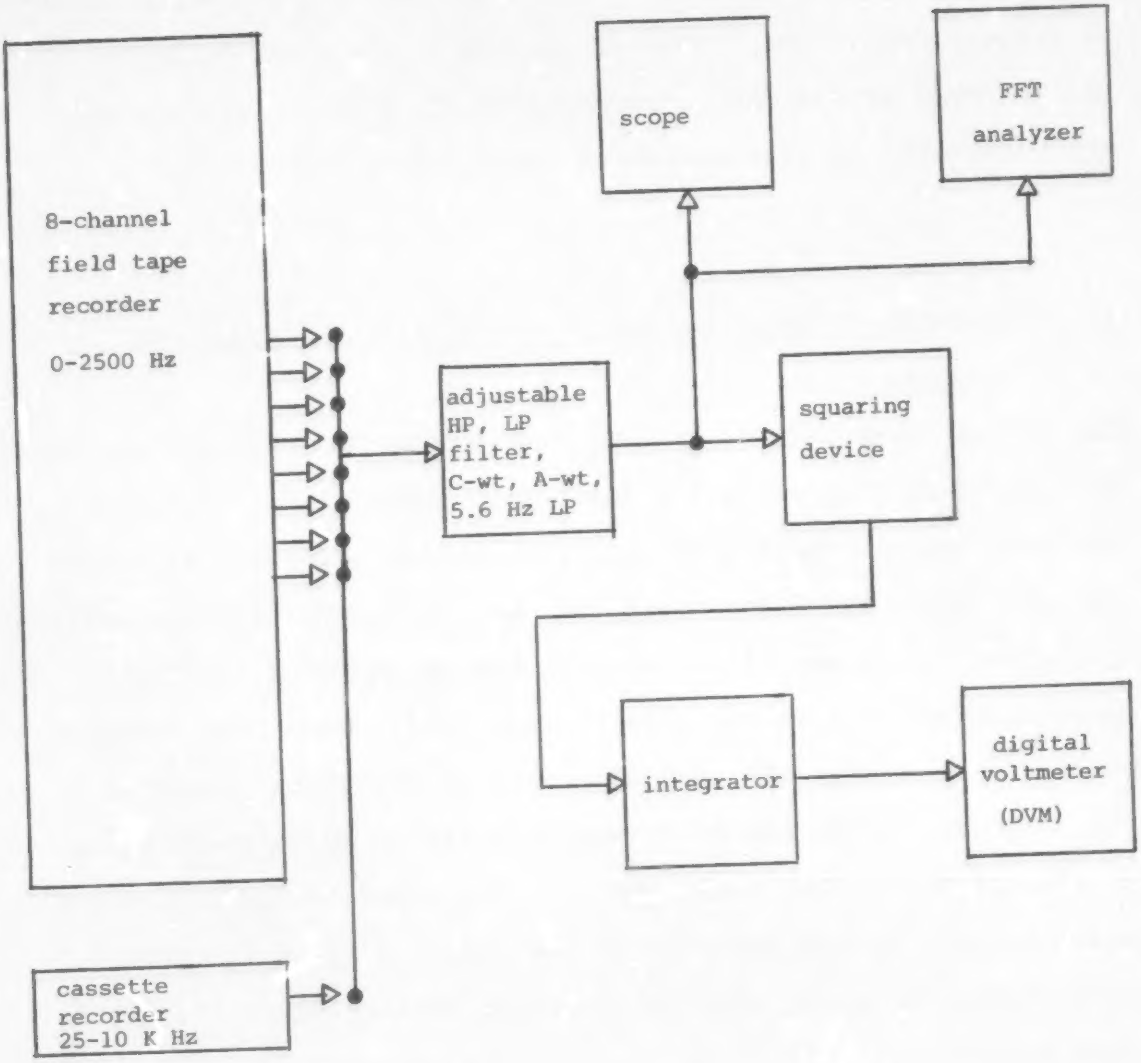
scope
FFT analyzer
8-channel field tape recorder 0-2500 Hz
adjustable HP, LP filter, C-wt, A-wt, 5.6 Hz LP
squaring device
integrator
digital voltmeter (DVM)
cassette recorder 25-10 K Hz

Fig. A.3.4-1. Data Analysis System for Determining Blast Noise and Vibration Energy, SEL and VEL.

conventional DC digital voltmeter. Initially a log converter was placed between the integrator and the digital voltmeter so that the digital voltmeter would read directly in decibels. However, the small but important DC drift in the output of the logging device created unacceptable errors in the digital voltmeter readout. With the removal of the log unit, the voltmeter reading was converted back into decibels by simply computing the log of the signal with a hand calculator.

To calibrate the SEL/VEL meter, a reference tone from the tape recorder was played through the system and the signal was integrated for exactly 10 seconds with the integrator switch in the 10-second position. The output answer then became the reference for the 1-second position on the integrator. In this way all impulse signals, irrespective of their duration, were automatically normalized to 1-second integration time.

Determining the SEL/VEL of the various signals placed the most stringent requirements on the dynamic range and DC drift of the tape recorder. Initially it appeared desirable to compute the vector sum of the vibration signals from the three mutually perpendicular velocity pickups. The idea was fine, but it proved almost impossible to execute accurately. To enhance the usable dynamic range of the tape recorder by 10 dB, three identical 4-pole (24 dB per octave) low-pass filters set at 200 Hz were inserted in the three signal lines from the tape recorder to the vector-summing device. The low-pass filters helped the situation, but there were two remaining problems that finally discouraged the use of the vector-summing device. It has been pointed out how important it is to maintain a near zero offset voltage (immediately prior to the blast signal) when entering the squaring device and integrator. This problem exists for a signal entering the vector-summing device, except now one must maintain zero offset for three signals instead of just one. This proved to be a problem for signals with a fair to poor signal-to-noise ratio. The second problem had to do with the primary wow and flutter component from the tape recorder. The vector-summing device saw this frequency component arrive in phase from all three channels simultaneously and thus it squared the undesirable wow signal and summed all three signals in phase. It was finally concluded that the most accurate value for the vector sum would be arrived at by mathematically summing the output signal from the digital voltmeter for the three individual components analyzed separately. In situations where the signal-to-noise ratio was particularly poor, the SEL/VEL would be determined for the particular blast event; a section of the tape immediately before the blast would be analyzed for precisely the same amount of time, and the resultant answer on the digital voltmeter subtracted from the results obtained during the blast. Whenever the output voltage from the integrator was not at least twice the value of the background noise, the results were not reported. Fortunately, this 3 dB signal-to-noise ratio situation was seldom encountered.

The results of the SEL/VEL analysis of all recorded signals utilizing a variety of input filters and weighting networks is contained in Table A.4.3-2. Comparison of the SEL/VEL results with other descriptors is summarized in Section 3.4.

The peak values for the lateral, transverse, and vertical vector sums were difficult to obtain accurately from the tape-recorded signals for the reasons just discussed. This loss of information is not considered significant since the peak vector sum is normally equal to the maximum peak of any one of the three components.

The C-weighted SEL air blast data was difficult to obtain outdoors because the measuring microphone was also required to measure the 1 Hz air blast peak, which was found to be typically more than 25 dB above the C-weighted SEL.

A.4 Data Presentation and Interpretation

A.4.1 Time History Records

The time history of the blast shows the separation of the groundborne wave outside to the airborne wave outside and the effect each one has on the inside of the dwelling. Figure A.4.1-1 is a sample oscilloscope recording of blast 15 displaying the lateral, transverse, and vertical velocity measurements outside (channels 1, 2, and 3, respectively); the airborne wave outside (channel 4); the vertical floor acceleration inside (channel 5); and the lateral, transverse, and vertical floor velocity inside (channels 6, 7, and 8,

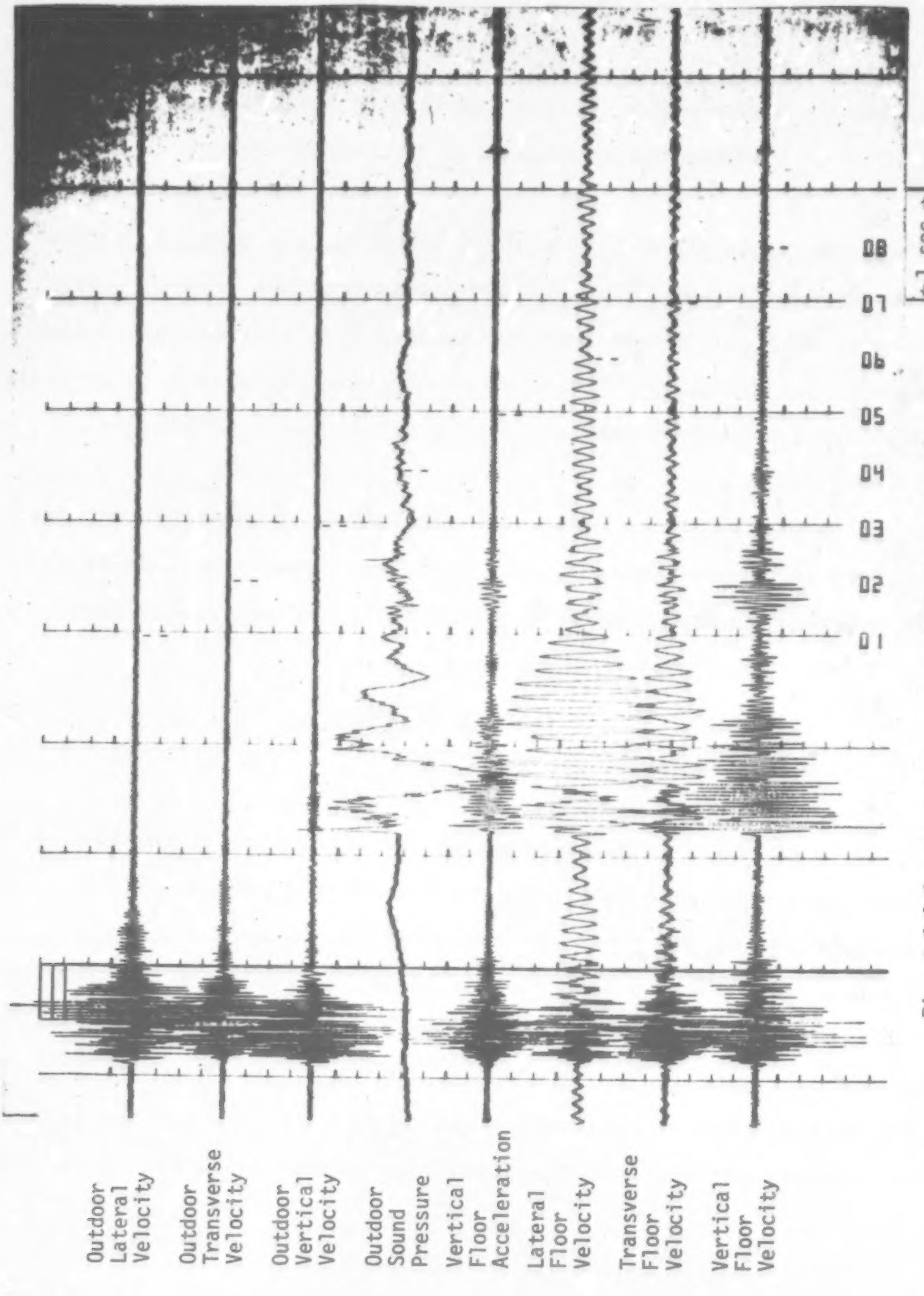

Fig. A.4.1-1. Oscillograph Record of Blast No. 15

respectively. All eight traces were made simultaneously, with the vertical lines representing one-second time intervals. No absolute amplitude scale was intended for these oscillograph records, only the time history. However, the three outdoor velocity traces (1, 2 and 3) have twice the signal amplification of the indoor velocity traces (6, 7 and 8). This time history shows the arrival of the ground-borne wave outside and the resultant vibration inside the house. This signal decays until the airborne wave arrives and initiates a second vibration inside the house. Figure A.4.1-2 is an oscillograph recording of blast 7 displaying the lateral velocity outside (channel 1), the outdoor airborne wave (channel 4), and the indoor sound pressure (channel 5). This time history shows the arrival of the ground-borne wave outside and the resultant noise inside due to the vibration of the house and possibly the rattling of bric-a-brac. The airborne wave arrives later and passes into the house nearly unchanged. The walls of the home filter out the high-frequency content of the sound wave but are transparent to the low-frequency (approximately 1 Hz) component. Therefore, the overall shape of the time trace of the indoor sound pressure is identical to that of the outdoor sound pressure, but the jaggedness due to the higher frequencies present in the outdoor trace is absent from the indoor trace. Oscillograph records of blast 1 through 18 are included in Appendix B.

The most important information given by the oscillograph records is the time history, which permits correlation between the outdoor

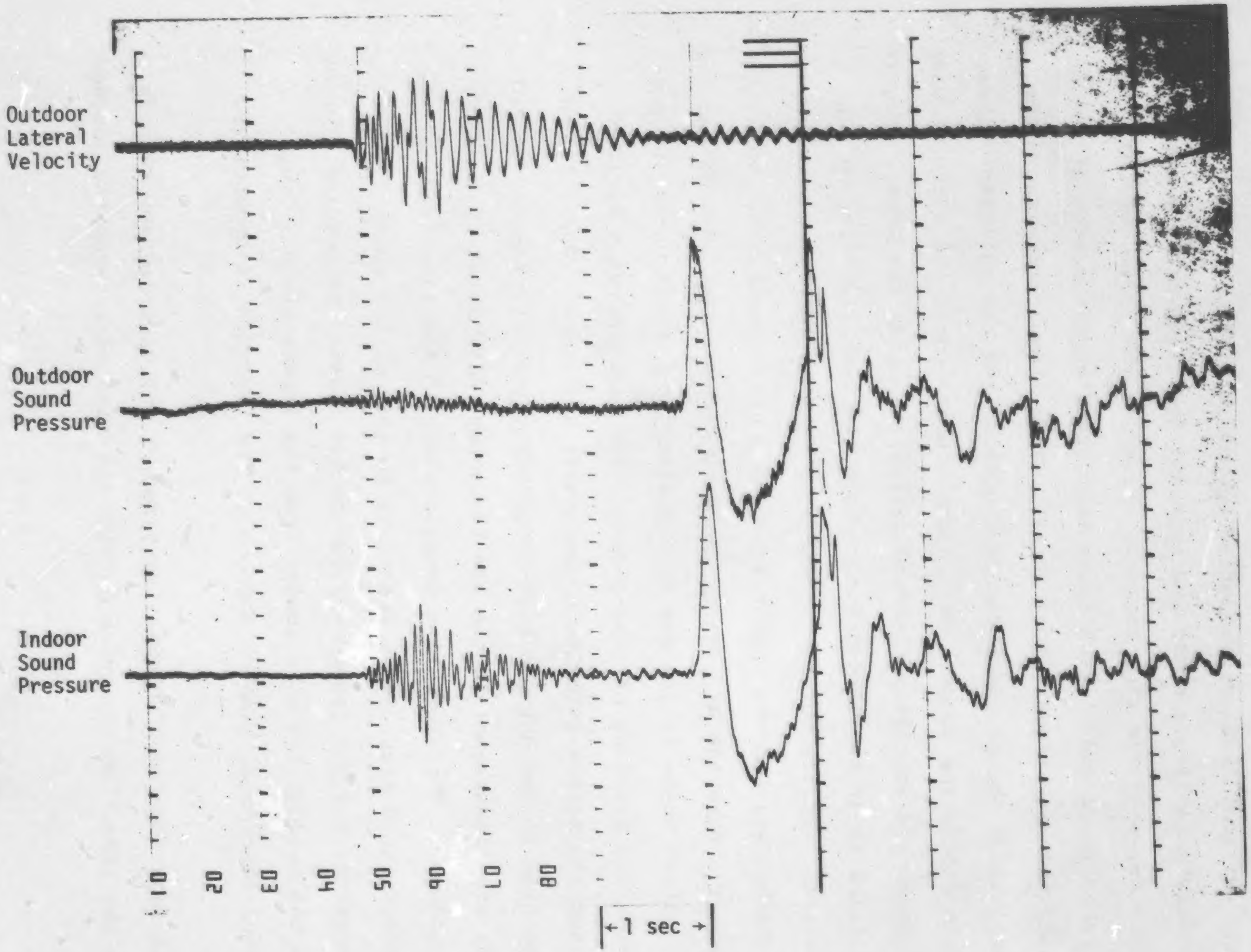

Fig. A.4.1-2. Oscillograph Record of Blast No. 7

signal and the resultant indoor signals. By examining the oscillograph records, a sharp line could be drawn in most cases between the indoor sound and vibration caused by the ground wave and the indoor sound and vibration caused by the air wave. It was surprising to find that the ground vibration measured outside the dwelling caused the dwelling walls and floors to vibrate for a longer period than the signal duration in the ground outside. The same phenomenon happens with the blast wave, but it is not as obvious from the oscillograph records. It has been pointed out elsewhere in this report that it is necessary to separate the blast site from the dwelling to be monitored by a distance of about 1000 meters in order to have a clear separation of the signals produced by the ground wave and the air blast. At these great distances the signals were very low, and sometimes interference from footfalls and other activity in the dwelling caused unwanted signals close to the blast events of interest. The oscillograph records were of great assistance in determining the exact time for signal analysis, and thereby eliminating unwanted sound and vibration signals during the blast. A few oscillograph records showed ground waves arriving at different times due to different paths in the earth (see blasts 7, 15, and 18). Monitoring the indoor vibration in a typical dwelling within 300 meters of a blast event made it impossible to separate the contributions of ground-borne energy and the airborne blast wave. When the distance between the blast event and the instrumented dwelling was increased, the oscillograph records made the relative importance of the ground and air waves more apparent.

A.4.2 Frequency Spectra

Frequency spectra of selected signals from blast 15 are shown in Figs. A.4.2-1 through A.4.2-9. There is no absolute full scale for these spectra although they are accurately marked in 10 dB ("DB" on left side of figures) increments with a total range of 60 dB. The absolute magnitude of these spectra was determined by automatically plotting the detailed spectra on large graph paper. The frequency range noted by "F" along the bottom of the spectra is linear from 0 to 200 Hz for all. The frequency spectra of the outdoor lateral and vertical ground velocities are displayed in Figs. A.4.2-1 and A.4.2-2, respectively.

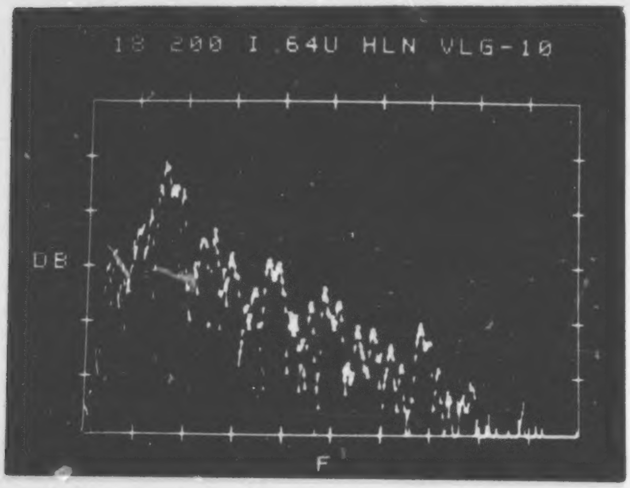

Fig. A.4.2-1 Outdoor lateral ground velocity for blast no. 15.

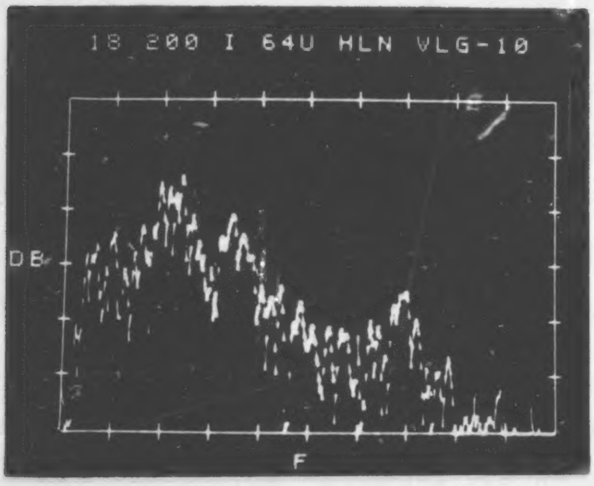

Fig. A.4.2-2 Outdoor vertical ground velocity for blast no. 15.

Fig. A.4.2-3 is a frequency spectrum of the outdoor sound pressure. These three spectra demonstrate that the ground wave contains the major portion of its energy between 5 and 100

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Hz. The frequency spectra of the indoor lateral floor velocity due to the ground-borne wave and airborne wave are shown in Figs. A.4.2-4 and A.4.2-5, respectively. These two spectra demonstrate that the frequency content of the outdoor ground-borne and airborne waves is transferred into the dwelling vibration. Both spectra show a prominent frequency component at 8 Hz, even though this frequency component is not of major importance in the outdoor ground velocity or sound pressure. This frequency component is probably the resonant frequency of the floor in this horizontal direction. Figures A.4.2-6 and A.4.2-7 are frequency spectra of the vertical floor velocity due to the ground-borne wave and the airborne wave, respectively. These spectra also show higher frequency content due to the ground-borne wave than to the airborne wave. To ensure that there are no frequency components of the ground-borne

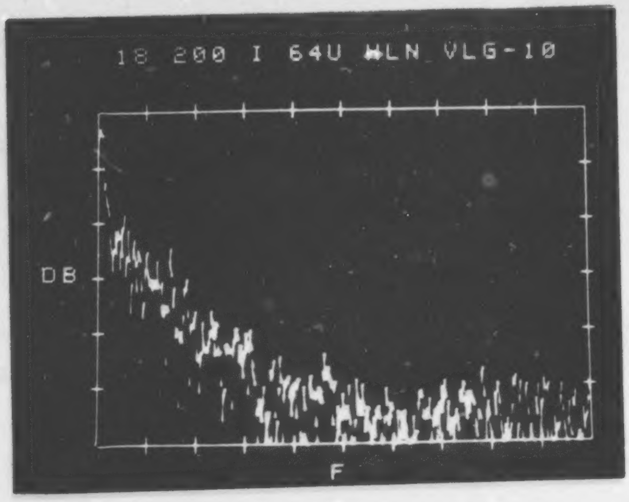

Fig. A.4.2-3 Outdoor sound pressure.

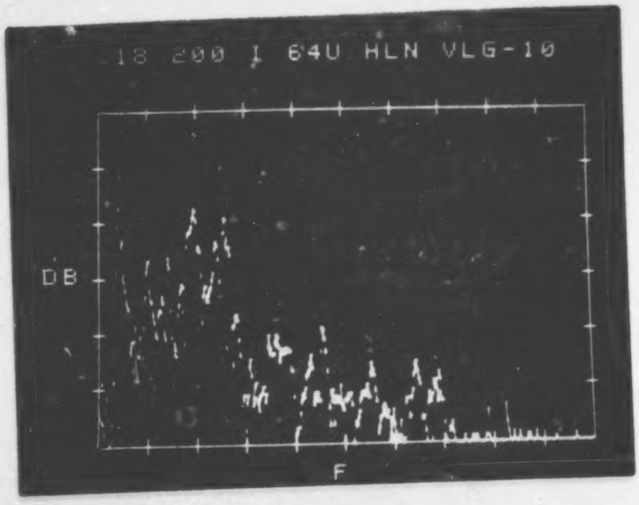

Fig. A.4.2-4 Indoor lateral floor velocity due to the ground wave.

wave or airborne wave below the 4 Hz cutoff of the velocity transducers, the acceleration frequency spectra of the vertical floor vibration due to the ground-borne and airborne waves were analyzed. These spectra are shown in Figs. A.4.2-8 and A.4.2-9. The ground-borne wave contains no significant energy below 5 Hz in the acceleration spectrum. The acceleration of the floor due to the airborne wave does show a frequency component at 1 Hz, but this component is of little significance compared to the energy between 10 and 50 Hz.

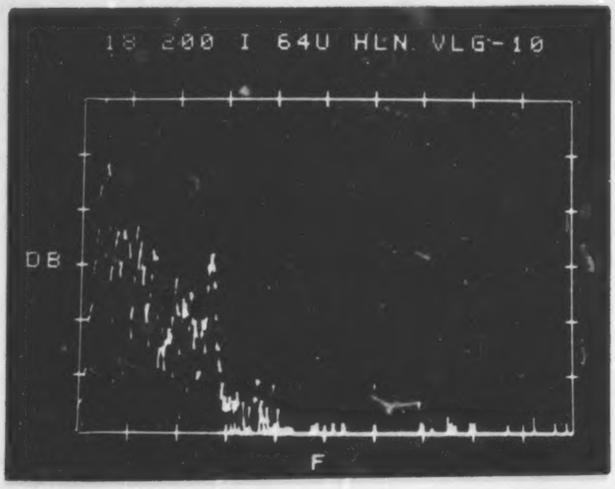

Fig. A.4.2-5 Indoor lateral floor velocity due to the air wave.

Some spectra show a relatively high level component near 0 Hz. This very low frequency information is caused by low-frequency (DC) drifting in the total record-reproduce system and should be ignored when viewing the spectra.

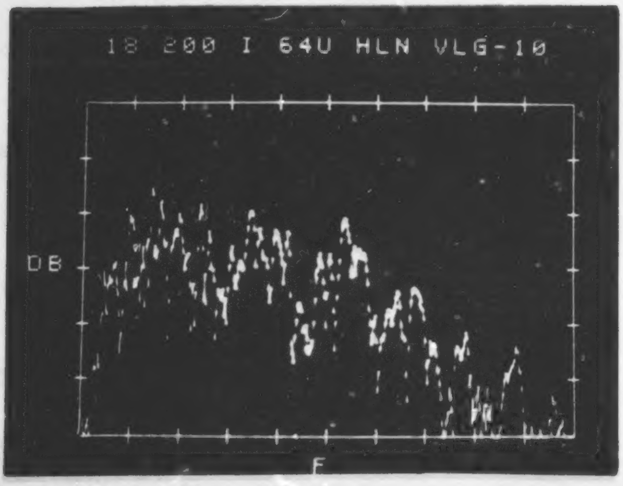

Fig. A.4.2-6 Indoor vertical floor velocity due to the ground wave.

The frequency spectrum obtained with the FFT narrowband analyzer was examined in detail for each signal from all recorded blast events. A careful study of all of the outdoor gound velocity spectra showed that the bandwidth of ground vibration was encompassed between 5 and 200 Hz. The spectra from the air wave had a very prominent component at 1 Hz (± 0.5 Hz) and a very sharp roll-off above and below this frequency. Examination of the indoor blast noise and vibration spectra showed energy at the same frequencies found outside. A vibration criterion was established for a typical dwelling by determining the frequency bandwidth at which the indoor floor velocity signal levels were higher than the ground velocity measured outside the same dwelling. A composite of all of the data suggests that the principal range of interest is from 5 to 50 Hz, with secondary resonances up to 200 Hz. This vibration criterion formulated the basis for determining the transfer function utilizing

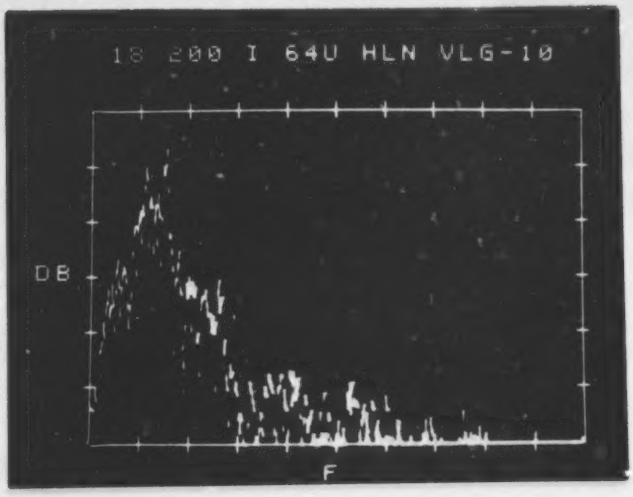

Fig. A.4.2-7 Indoor vertical floor velocity due to the air wave.

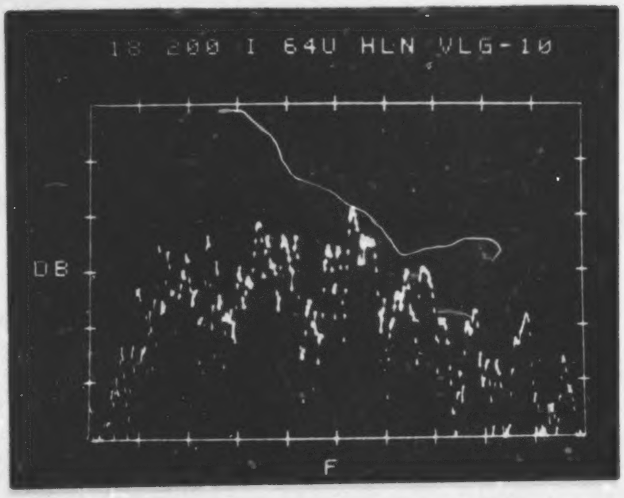

Fig. A.4.2-8 Indoor vertical floor acceleration due to the ground wave.

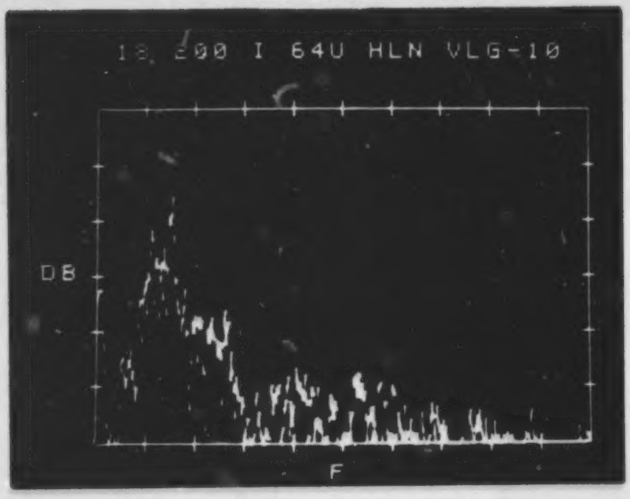

Fig. A.4.2-9 Indoor vertical floor acceleration due to the air wave.

various descriptors with different weighting or frequency characteristics. The air wave had to be treated in a somewhat different fashion because of the very prominent 1 Hz component. It was determined that the 1 Hz component inside the dwelling was typically on the same level as the 1 Hz component outside the dwelling. It was also found that the 1 Hz component did not excite a typical dwelling at 1 Hz. Therefore, a different criterion for evaluating the indoor vibration caused by the outdoor air wave was established. This criterion was specified as follows: Determine the peak level in the indoor velocity measurement above 4 Hz and then determine the frequency bandwidth at the 20 dB down points at either side of this peak component. By comparing the various velocity spectra measured on the floor of the dwelling, it was found that a frequency bandwidth extending from 4 to 50 Hz would adequately describe the spectrum required to correlate with the outdoor air wave. Inasmuch as this data was obtained at a considerable distance (typically 1000 meters) from the blast, it was considered important to extend the upper frequency range to 200 Hz to encompass the higher frequency energies that one would expect to find in a dwelling very close to a blast.

Thus far the transfer function from the ground-borne wave to the indoor floor vibration and the airborne wave to the indoor floor vibration have been discussed. There are two additional transfer functions that are of significance: the outdoor air wave versus the indoor air wave or noise and the outdoor ground vibration that causes noise inside the dwelling. The outdoor air wave entering a typical dwelling is not attenuated at the peak frequency in the vicinity of 1 Hz. This 1 Hz component is inaudible to humans. The frequency range of principal interest would be the A-weighted narrowband spectra. It was interesting to learn that the A-weighted narrowband spectrum was nearly flat over the frequency range extending from 1 to 2000 Hz. In most instances the maximum energy after the spectrum had been A-weighted coincided with the resonant frequencies of the dwellings in the 10 to 200 Hz range. The A-weighted recordings were made inside the dwellings during each blast event to record the rattling effects from windows, bric-a-brac on shelves, dishes in cupboards, and the dwelling in general. These are all non-linear effects that are not readily scaled and thus it is difficult to predict what the A-weighted sound level will do with higher or lower air blast impingement upon the dwelling.

To an observer standing outside a dwelling the passing of the ground wave from a blast event appears very insignificant. The measurement of the sound outside the dwelling confirms this. On the other hand, the microphone signal inside the dwelling showed a substantial noise generated by the dwelling being shaken by the ground wave. The prominent frequencies in the airborne spectrum inside the dwelling were identical to the floor vibration frequencies found in the dwelling. Part of the experiment was to make limited measurements of the velocity of the walls during the arrival of both the ground and air waves. From these measurements, it was concluded that the floor velocity and the wall velocity were very similar in magnitude and frequency. Both surfaces contributed to the sound in the room and gave similar characteristics to the sound spectra in the room during the passing of the ground wave.

A.4.3 Single-Number Descriptors

Section A.3 discussed in detail the data analysis procedures used to determine a wide variety of single-number descriptors for each of the blast measurements. The results of this analysis utilizing the various descriptors are presented in Tables A.4.3-1 through A.4.3-6. The maximum instantaneous peaks of each blast noise and vibration signal shown in Table A.4.3-1 were determined from the original calibrated oscillograph records that utilized an expanded time scale to produce records approximately 1 meter in length. These long and bulky records were easy to read but difficult to reproduce in the report. The oscillograph records shown in Appendix B are the same data presented in a compressed format.

All recorded data on blast noise and vibration were also passed through a 4 to 200 Hz filter. The signal from the filter was

Table
A.4.3-1. Maximum instantaneous peaks of blast events (except acceleration weighted through a 5.6 Hz low-pass filter from .5 Hz to 200 Hz). Data in dB re 1 m/sec for velocity, re 1 g for acceleration and re 20 µ pascals for sound pressure level.

	Outdoor Ground Velocity			Outdoor	Indoor Sound		Lateral		Transverse		Vertical		Vertical Floor Acceleration	
Blast No.	Lat. dB re m/sec	Trans. dB re m/sec	Vert. dB re m/sec	Sound dB re 20 µ pa	ground dB re 20 µ pa	air dB re 20 µ pa	ground dB re m/sec	air dB re m/sec	ground dB re m/sec	air dB re m/sec	ground dB re m/sec	air dB re m/sec	ground dB re 1 g	air dB re 1 g
1	-	-	-	-	87.0	106.5	-	-	-	-	-59.5	-	-52.2	-
2	-48.5	-49.5	-52.9	120.0	99.0	121.0	-	-	-	-	-49.1	-	-32.8	-51.1
3	-47.2	-46.3	-52.9	117.6	110.6	116.1	-	-	-	-	-45.0	-59.0	-46.1	-
4	-55.8	-52.5	-55.3	112.0	103.0	113.5	-	-	-	-	-51.0	-65.0	-41.4	-
5	-58.5	-61.3	-58.5	104.5	94.0	106.2	-56.9	-	-54.3	-	-56.7	-	-	-
6	-57.4	-57.8	-55.8	114.3	97.5	115.2	-58.1	-	-63.3	-	-55.4	-	-	-
7	-43.8	-42.7	-48.2	122.1	115.2	124.0	-40.1	-57.8	-46.9	-63.3	-40.8	-60.8	-	-
8	-69.1	-73.3	-73.3	112.2	-	113.0	-70.9	-77.0	-77.4	-77.4	-74.0	-64.9	-	-
9	-68.5	-69.8	-71.4	114.0	-	112.7	-68.0	-75.4	-68.5	-75.8	-63.7	-59.3	-	-
10	-70.2	-70.8	-69.7	111.9	86.6	115.5	-73.5	-68.8	-73.5	-77.7	-72.1	-63.7	-	-
11	-69.8	-72.3	-68.2	113.6	84.7	114.4	-71.3	-70.3	-74.4	-79.4	-70.2	-74.4	-	-
12	-57.3	-63.1	-63.8	-	107.3	121.7	-62.8	-73.4	-	-	-52.4	-	-	-
13	-68.9	-63.3	-70.3	99.4	-	100.0	-62.9	-70.9	-57.6	-73.1	-61.7	-68.0	-	-
14	-75.4	-73.4	-74.9	123.8	-	-	-69.8	-76.9	-70.5	-72.1	-70.1	-76.9	-57.1	-56.8
15	-66.4	-65.8	-67.4	119.3	-	-	-63.8	-60.8	-65.3	-68.2	-60.5	-59.9	-49.4	-47.6
16	-64.5	-67.3	-67.7	115.9	-	-	-66.5	-81.3	-70.8	-79.8	-64.9	-68.0	-49.8	-53.7
17	-76.5	-73.7	-74.8	107.7	-	-	-74.6	-76.9	-71.6	-82.9	-74.6	-72.1	-61.1	-58.9
18	-72.0	-73.0	-76.9	116.8	-	-	-75.0	-70.3	-71.4	-71.7	-70.9	-70.6	-	-

Table A.4.3-2. The SEL and VEL results of blast events over a 4 Hz to 200 Hz filter (except accleration weighted through a 5.6 Hz low pass filter from .5 Hz to 200 Hz). Data in dB re 1 m/sec for velocity, re 1 g for acceleration and re 20 µ pascals for sound pressure level.

	Outdoor Ground Velocity			Outdoor Sound	Indoor Sound		Indoor Floor Velocity						Vertical floor Acceleration	
							Lateral		Transverse		Vertical			
Blast No.	Lat. dB re m/sec	Trans. dB re m/sec	Vert. dB re m/sec	Sound dB re 20 µ pa	ground dB re 20 µ pa	air dB re 20 µ pa	ground dB re m/sec	air dB re m/sec	ground dB re m/sec	air dB re m/sec	ground dB re m/sec	air dB re m/sec	ground dB re 1 g	air dB re 1 g
1	-	-	-	-	79.8	88.0	-	-	-		-72.5	-75.0	-66.0	-
2	-61.3	-61.0	-64.3	103.8	88.5	99.8	-	-	-		-62.1	-76.0	-44.2	-59.0
3	-62.4	-61.8	-70.5	96.4	95.0	88.6	-	-	-		-61.6	-87.0	-57.3	-
4	-67.4	-65.0	-69.5	97.1	90.5	99.8	-	-	-		-61.5	-72.0	-50.2	-
5	-70.4	-71.0	-69.0	90.2	82.4	90.5	-67.7	-	-65.2		-67.3	-	-	-
6	-68.4	-68.2	-67.0	97.0	90.0	100.6	-67.6	-	-71.1		-65.2	-	-	-
7	-55.0	-58.1	-65.0	9[illegible].8	98.8	98.8	-50.6	-	-60.7		-56.6	-	-	-
8	-79.7	-85.9	-84.0	95.6	77.5	96.3	-84.0	-87.0	-87.0	-87.0	-80.0	-77.0	-	-
9	-77.5	-78.0	-80.0	97.8	76.2	98.9	-79.2	-84.0	-80.7	-78.5	-75.0	-74.0	-	-
10	-73.3	-75.0	-77.2	101.0	77.5	105.3	-77.2	-68.2	-79.6	-81.8	-74.4	-65.6	-	-
11	-78.0	-84.1	-81.5	97.9	72.8	101.0	-80.4	-76.4	-87.4	-88.0	-82.2	-83.4	-	-
12	-70.1	-75.7	-74.3	-	85.4	96.5	-74.1	-80.2	-	-	-66.4	-85.6	-	-
13	-75.6	-73.3	-78.0	89.4	75.0	91.0	-71.5	-	-66.7	-	-70.7	-78.2	-	-
14	-82.2	-82.2	-84.0	106.9			-78.5	-87.8	-78.5	-88.7	-78.2	-87.0	-66.0	-66.0
15	-77.0	-77.2	-78.0	102.4			-75.0	-67.2	-76.5	-95.0	-72.7	-69.9	-60.6	-56.5
16	-75.5	-78.5	-80.4	102.2			-79.5	-91.0	-82.1	-88.4	-78.2	-75.1	-66.0	-65.4
17	-85.0	-84.2	-86.6	92.0			-86.2	-87.0	-83.5	-92.5	-83.2	-80.6	-70.0	-69.0
18	-81.6	-85.2	-89.7	99.6			-85.5	-80.0	-83.8	-82.7	-83.0	-81.7	-	-

Table A.4.3-3. SEL of blast events through a C-weighting network or an A-weighting network. All in dB re 20 μ pascals.

Blast No.	Outdoor C-Weighted SEL Air Wave	Indoor C-Weighted SEL Ground Wave	Indoor C-Weighted SEL Air Wave	Indoor A-Weighted SEL Air Wave
1	-	75.2	66.0	-
2	-	84.2	85.2	-
3	-	83.3	75.8	-
4	-	81.6	83.2	-
5	77.6	76.5	71.7	54.7
6	-	79.7	80.8	52.5
7	83.6	90.0	83.0	55.9
8	-	71.2	82.3	49.5
9	83.9	71.7	81.5	54.0
10	92.1	72.5	86.4	51.7
11	85.2	69.5	78.1	48.7
12	-	82.5	71.2	-
13	-	68.2	71.2	-
14	101.2	-	-	61.7
15	92.5	-	-	49.9
16	88.1	-	-	44.7
17	83.6	-	-	47.3
18	87.9	-	-	54.2

Table A.4.3-4. Slow meter response of blast events through a 4 Hz to 200 Hz filter. Sound pressure data in dB re 20 µ pascals and velocity data in dB re 1 meter per second.

Blast No.	Outdoor Velocity in meters/sec L	V	Outdoor Sound Pressure in dB re 20 µ pa
1	-	-	-
2	-63.2	-66.0	98.0
3	-64.5	-73.0	90.0
4	-69.2	-70.2	91.0
5	-74.3	-71.0	82.5
6	-71.6	-70.0	89.0
7	-60.0	-67.2	94.3
8	-80.5	-86.0	91.0
9	-80.2	-83.5	94.0
10	-75.0	-79.8	98.2
11	-79.3	-83.8	93.0
12	-71.0	-76.0	-
13	-79.0	-81.0	83.2
14	-85.2	-87.0	103.0
15	-78.9	-80.0	98.0
16	-77.0	-82.0	99.0
17	-86.8	-88.8	88.0
18	-83.2	-92.0	95.0

Table A.4.3-5. Slow meter response of blast events through a C-weighting network. Sound pressure data in dB re 20 μ pascals, and velocity data in dB re 1 meter per second.

Blast No.	Outdoor Velocity in meters/sec		Outdoor Sound Pressure in dB re 20 μ pa
	L	V	
1	-	-	-
2	-66.9	-69.6	89.8
3	-74.8	-78.7	82.5
4	-72.9	-73.8	81.9
5	-78.4	-73.7	73.7
6	-76.8	-73.3	80.7
7	-72.4	-74.7	82.6
8	-76.5	-88.3	85.2
9	-85.1	-86.6	83.0
10	-78.4	-81.5	89.8
11	-82.2	-85.3	84.6
12	-73.8	-77.5	-
13	-85.4	-84.9	76.0
14	-93.8	-99.0	93.0
15	-81.8	-81.9	91.0
16	-80.7	-84.4	87.0
17	-91.4	-90.8	82.0
18	-89.1	-95.4	87.0

Table A.4.3-6. Outdoor sound pressure measurements of blast events made by Illinois Environmental Protection Agency in 1976 on quarry or coal mine property. All in dB re 20 μ pascals

Blast No.	Distance (meters)	Max Charge Per Delay (K grams)	Peak Sound Pressure Level	SEL 4-200 Hz	Slow Response 4-200 Hz	Slow Response C-weighted
1	130	30.8	117	103.4	100	98
2	229	30.8	[illegible]	105.5	100	97
8	396	30.8	132	110.7	110	109
9	254	61.2	127	113.5	112	105
10	315	30.8	131	108.4	105	102.5
11	372	30.8	133	107.4	104	100
12	396	30.4	115	100.2	96	95.5
19	512	95.2	123	108.6	106.5	99
20	512	95.2	121	100.5	103.2	95.3
21	512	136.1	131	106.5	106.8	103.6
22	376	381.0	136	120.5	118.2	110.7
23	396	340.2	127	117.1	114	106.0
24	152	385.6	133	116.0	113.5	111.5
25	412	476.3	140	125.0	122.1	114.8
26	412	476.3	145	130.3	128.5	120.7

squared and integrated with a true integrator having a 1-second time constant to obtain SEL or VEL. This data is presented in Table A.4.3-2.

The sound pressure level measurements recorded both inside and outside were sent through a standard C-weighted network and analysed to obtain CSEL. The A-weighted sound level recorded inside the dwelling was analyzed in the same manner. This reduced data is presented in Table A.4.3-3.

All outdoor sound data and many outdoor velocity measurements were passed through a conventional sound-level meter containing an external band-pass filter from 4 to 200 Hz. The maximum meter reading on slow response was recorded and the results are presented in Table A.4.3-4.

A similar experiment was conducted utilizing the conventional C-weighting network on the sound-level meter. Again, the maximum reading obtained with a slow meter response is shown in Table A.4.3-5.

These various descriptors were also used to analyze the outdoor air blast sound recordings made by Illinois EPA. The results of the analysis are shown in Table A.4.3-6.

In addition to the blast noise and vibration measurements taken inside and outside the selected dwellings, data was obtained to describe the physical characteristics of the dwelling, weather conditions, the distance between the blast and the instrumented dwelling, and the blast configuration. These data are presented in Appendix B together with the sound and vibration results for each blast. The information is also summarized in Table A.4.3-7.

Table
A.4.3-7. Physical data on quarry blasts measured by Kamperman Associates Inc. during August, September and October, 1976

Blast No.	Distance from Blast (m)	Maximum charge/ delay (kg)	Total charge (kg)	Total time (msec)	Orientation from blast face	Wind speed (km/ sec)	Orientation of wind from blast	# of floors	Construction		
									Frame	Outer wall	Basement, concrete
1	1100	30.8	604	392	180°	9	0°	1	wood	brick veneer	half poured, half grade slab
2	457	30.8	695	392	45°	10	0°	1	wood	brick veneer	poured
3	1280	317.5	3975	-	45°	10	45°	2	wood	brick veneer	poured
4	549	59.0	824	168	135°	-	-	2	wood	brick veneer	poured
5	579	30.4	531	266	180°	16	90°	1	wood	brick veneer	poured
6	655	59.0	1190	266	180°	16	90°	1	wood	brick veneer	poured
7	1128	317.5	3954	-	180°	20	45°	1	wood	wood	block
8	1067	30.8	762	378	45°	24	0°	1	wood	wood	block
9	1006	61.2	1165	238	45°	24	0°	1	wood	wood	block
10	646	30.8	911	462	90°	16	0°	1	wood	brick veneer	poured
11	701	30.8	530	266	45°	24	0°	1	wood	brick veneer	poured
12	701	30.4	3039	1372	-	16	45°	Tri-level	wood	brick veneer	poured
13	610	30.4	882	408	90°	24	0°	2	brick	brick	block
14	1600	226.8	2555	210	0	20	0	2	steel	concrete block	slab
15	762	31.8	740	378	45°	8	45°	Tri-level	wood	wood	poured
16	716	31.8	529	210	45°	8	45°	Tri-level	wood	wood	poured
17	1067	30.8	579	350	45°	16	0°	1	wood	brick veneer	block
18	1128	30.8	419	266	135°	24	0°	1	wood	brick veneer	block

Downwind is 0°, upwind is 180°.

APPENDIX B

DETAILED TIME HISTORY OF 18 RECORDED STONE QUARRY BLAST EVENTS BY KAMPERMAN ASSOCIATES INC.

The signals and time (1-second markings) are displayed on a linear scale. The signal levels are not calibrated in absolute values. However, for any particular blast, the three outdoor velocity pickups have the same gain, the outdoor and indoor microphones (on traces 4 and 5) have the same gain, and the three indoor velocity pickups have the same gain (although it may be different from the outdoor pickups). The oscillograph records were displayed for easy viewing of the events vs time. The absolute peak values for each trace are summarized in Table A.4.3-1.

Quarry Blast No. 1

Distance from home to blast:	1100 meters
Direction of home from blast:	West
Home construction:	1 floor with half basement, wood frame, brick veneer
Wind direction out of the:	East-Northeast
Wind speed:	9 K meters/hour
Temperature:	26°C
Temperature profile:	Neutral
Cloud cover:	Hazy
Depth of blast below grade level:	45 meters
Total charge of blast:	604 K grams
Maximum charge per delay:	31 K grams/delay
Number of holes:	14
Depth of holes:	6 meters
Number of delays:	28
Time between delays:	12 mseconds
Total time of blast:	392 mseconds
Blast face orientation:	East

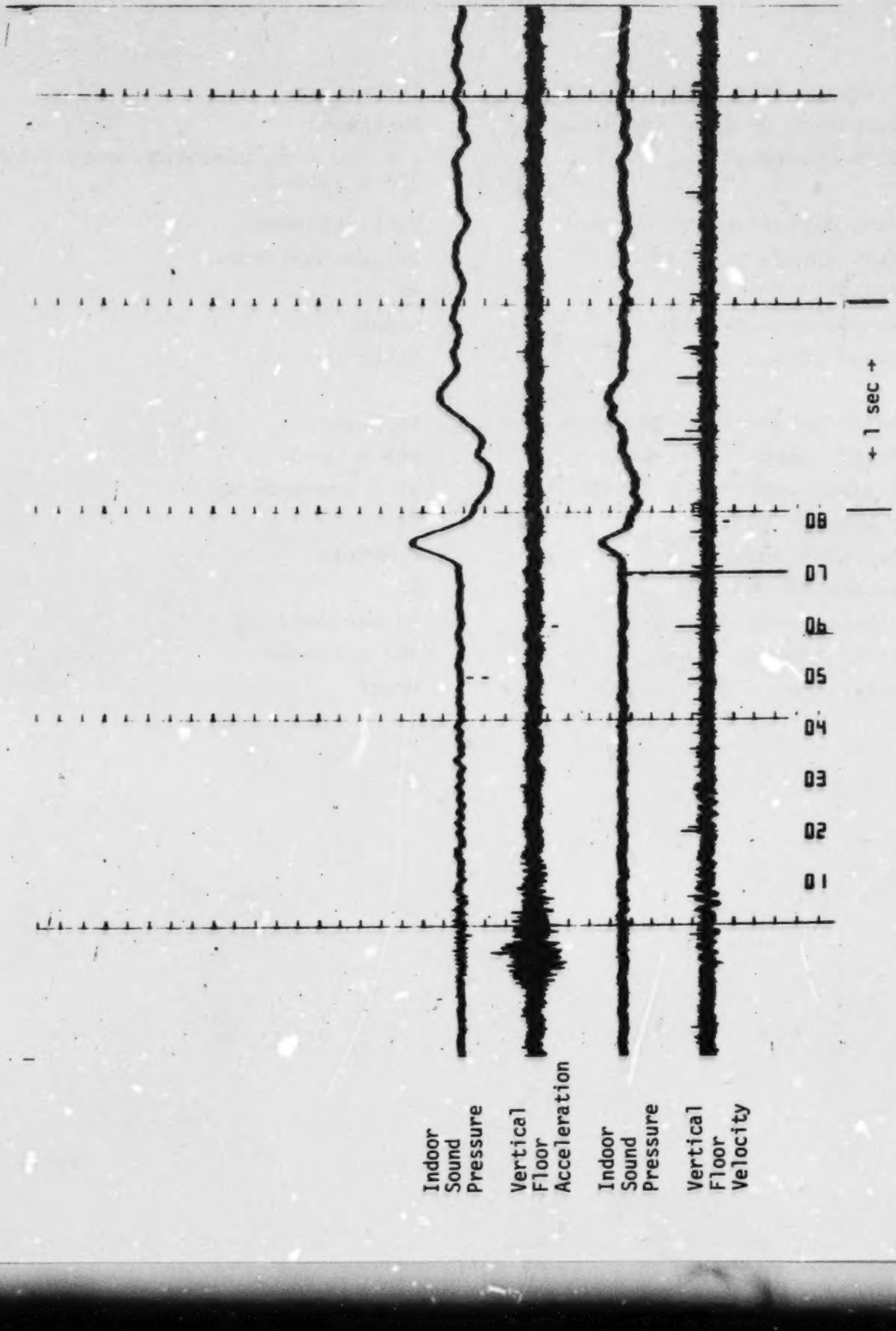

Fig. B-1. Oscillograph Record of Blast No. 1

Quarry Blast No. 2

Distance from home to blast: 457 meters
Direction of home from blast: Northwest
Home construction: 1 floor with basement, wood frame, brick veneer

Wind direction out of the: East-Northeast
Wind speed: 10 K meters/hour
Temperature: 28°C
Temperature profile: Lapse
Cloud cover: Clear

Depth of blast below grade level: 45 meters
Total charge of blast: 695 K grams
Maximum charge per delay: 31 K grams/delay
Number of holes: 14
Depth of holes: 6 meters
Number of delays: 28
Time between delays: 12 mseconds
Total time of blast: 392 mseconds
Blast face orientation: North

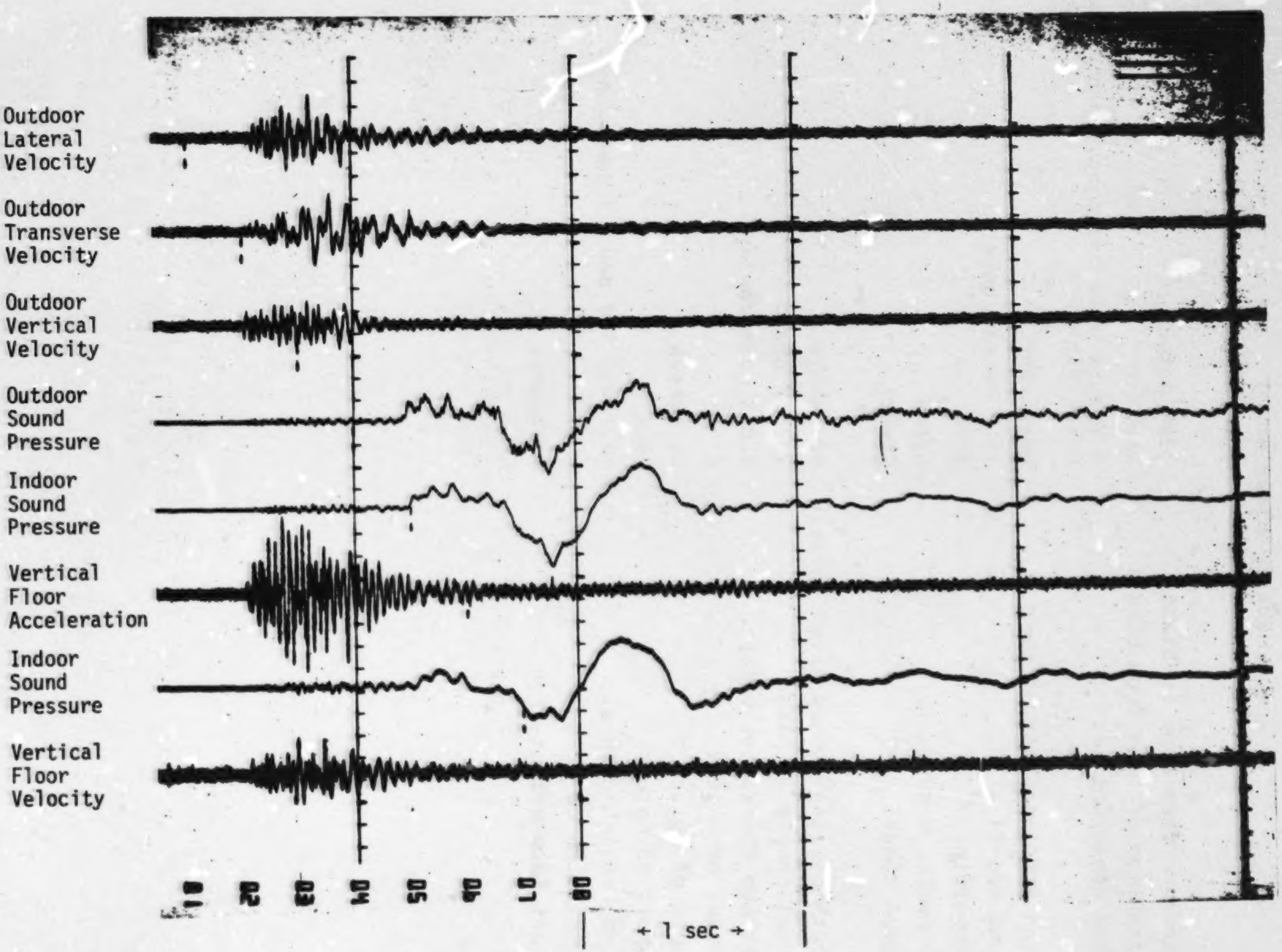

Fig. B-2. Oscillograph Record of Blast No. 2

Quarry Blast No. 3

Distance from home to blast:	1280 meters
Direction of home from blast:	West
Home construction:	2 floors with basement, wood frame, brick veneer
Wind direction out of the:	Northeast
Wind speed:	10 K meters/hour
Temperature:	33°C
Temperature profile:	Lapse
Cloud cover:	Clear
Depth of blast below grade level:	43 meters
Total charge of blast:	3975 K grams
Maximum charge per delay:	318 K grams/delay
Number of holes:	6
Depth of holes:	43 meters
Number of delays:	24
Time between delays:	40, 100, 120 and 150 mseconds
Total time of blast:	-
Blast face orientation:	Southeast

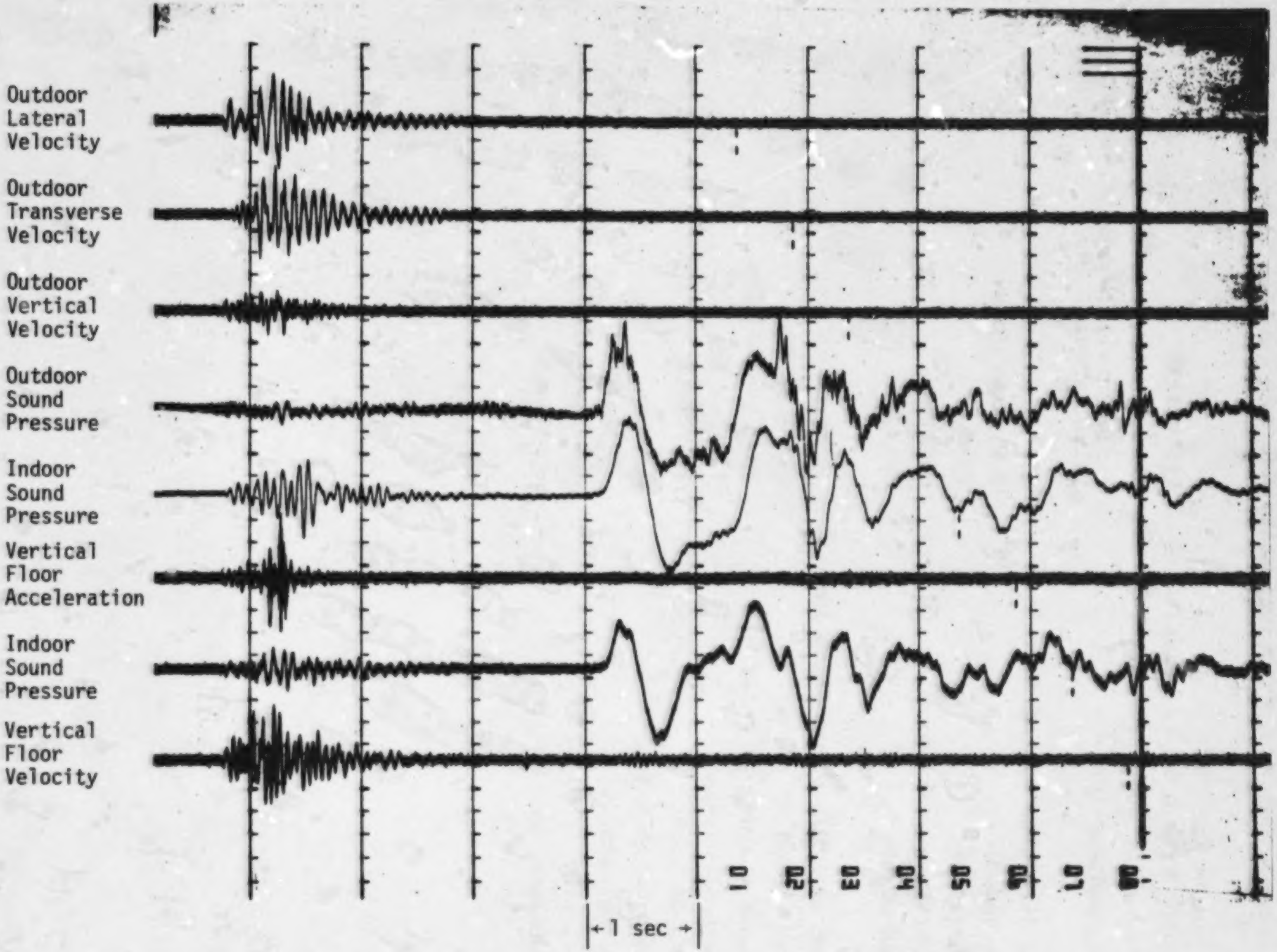

Fig. B-3. Oscillograph Record of Blast No. 3

Quarry Blast No. 4

Distance from home to blast:	*549 meters*
Direction of home from blast:	West
Home construction:	2 floors with basement, wood frame, brick veneer

Wind direction out of the:	None
Wind speed:	0 K meters/hour
Temperature:	27°C
Temperature profile:	Neutral
Cloud cover:	Hazy

Depth of blast below grade level:	70 meters
Total charge of blast:	824 K grams
Maximum charge per delay:	59 K grams/delay
Number of holes:	13
Depth of holes:	10 meters
Number of delays:	13
Time between delays:	14 mseconds
Total time of blast:	168 mseconds
Blast face orientation:	Southeast

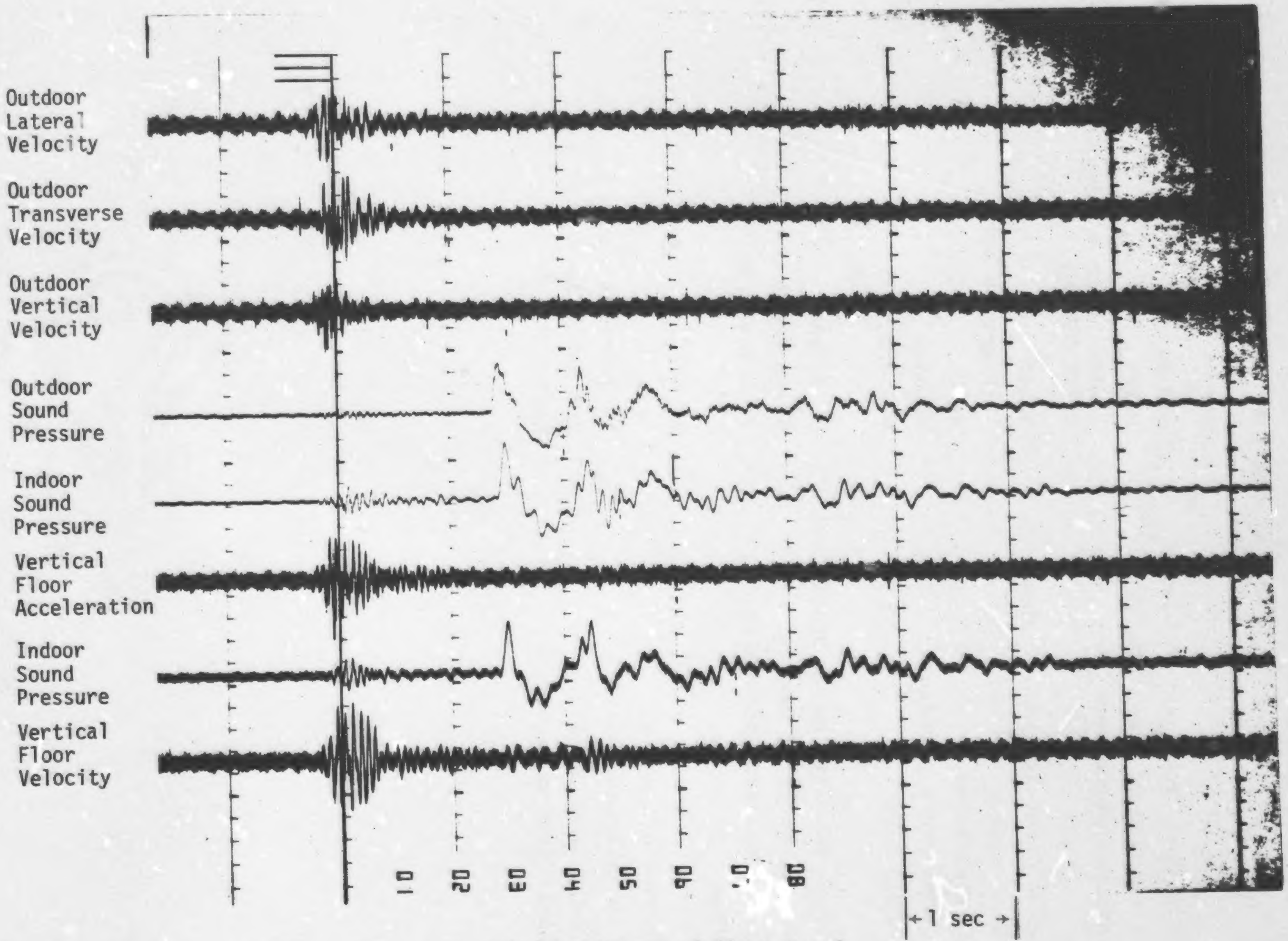

Fig. B-4. Oscillograph Record of Blast No. 4

Quarry Blast No. 5

Distance from home to blast:	579 meters
Direction of home from blast:	West
Home construction:	1 floor with basement, wood frame, brick veneer

Wind direction out of the:	South
Wind speed:	16 K meters/hour
Temperature:	24°C
Temperature profile:	Neutral
Cloud cover:	80% and hazy

Depth of blast below grade level:	70 meters
Total charge of blast:	531 K grams
Maximum charge per delay:	30 K grams/delay
Number of holes:	10
Depth of holes:	10 meters
Number of delays:	20
Time between delays:	14 mseconds
Total time of blast:	266 mseconds
Blast face orientation:	East

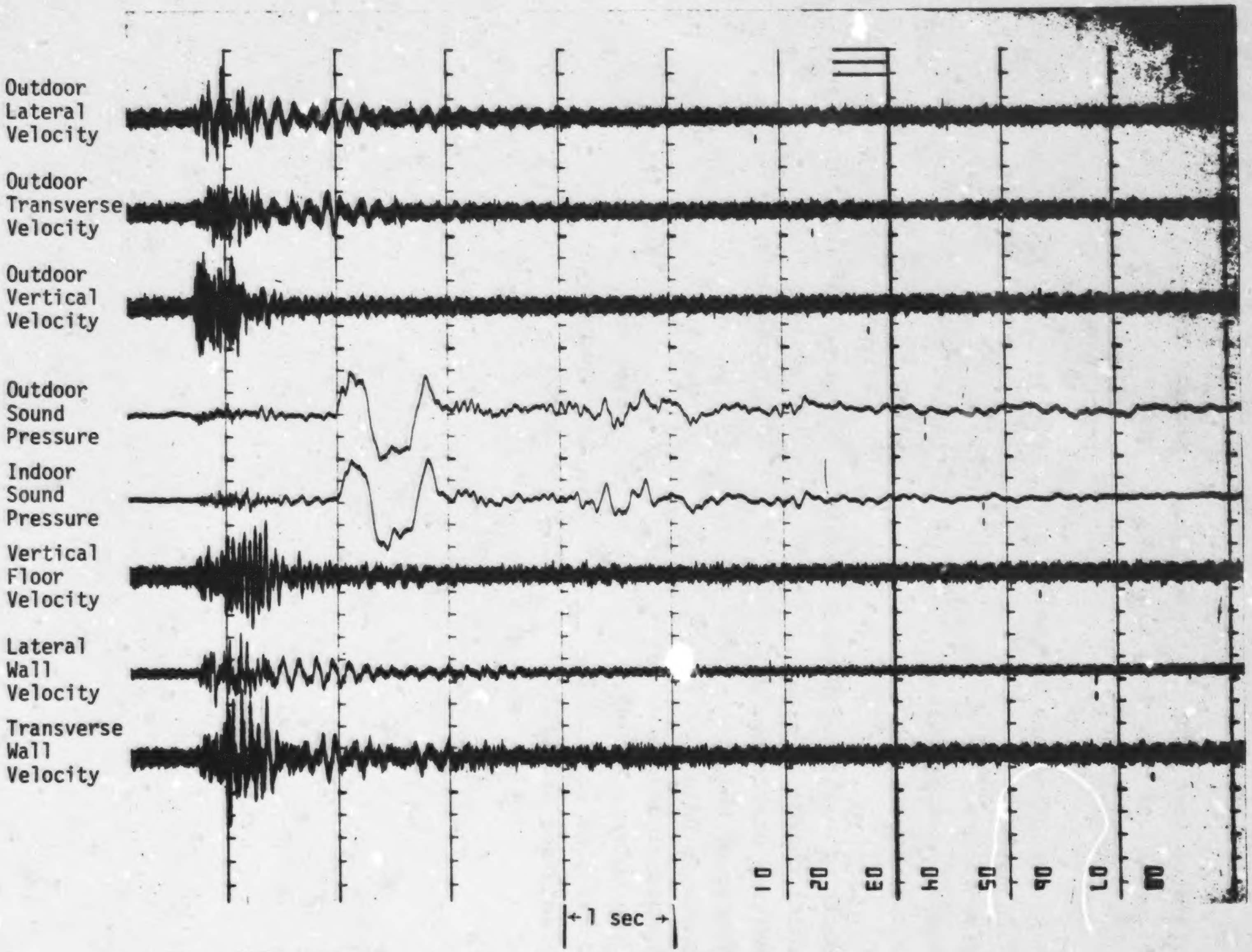

Fig. B-5. Oscillograph Record of Blast No. 5

Quarry Blast No. 6

Distance from home to blast: 655 meters
Direction of home from blast: West
Home construction: 1 floor with basement, wood frame, brick veneer

Wind direction out of the: South
Wind speed: 16 K meters/hour
Temperature: 27°C
Temperature profile: Lapse
Cloud cover: Clear

Depth of blast below grade level: 70 meters
Total charge of blast: 1190 K grams
Maximum charge per delay: 59 K grams/delay
Number of holes: 10
Depth of holes: 10 meters
Number of delays: 20
Time between delays: 14 mseconds
Total time of blast: 266 mseconds
Blast face orientation: East

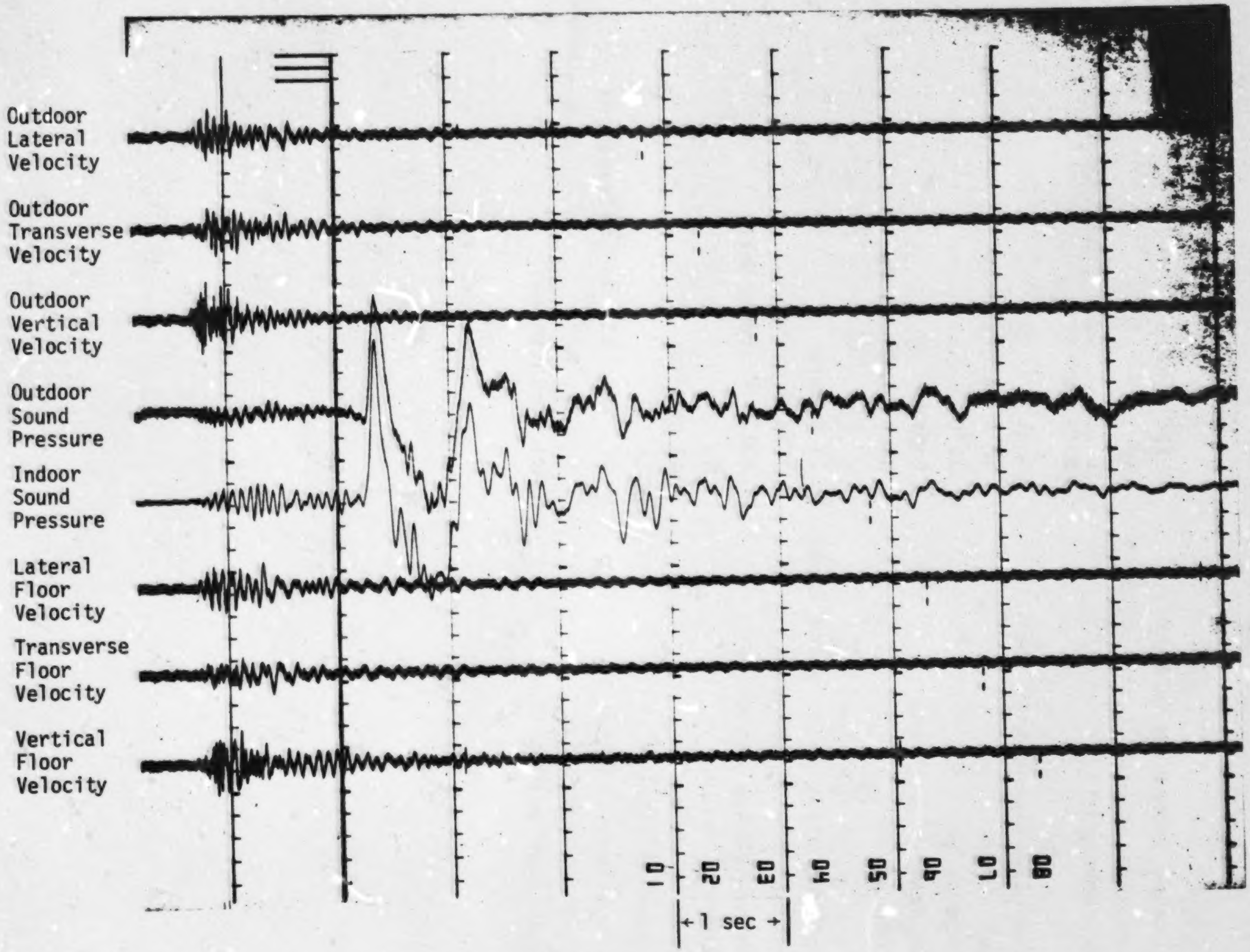

Fig. B-6. Oscillograph Record of Blast No. 6

Quarry Blast No. 7

Distance from home to blast:	1128 meters
Direction of home from blast:	West
Home construction:	1 floor, wood frame bungalow, full basement

Wind direction out of the:	South
Wind speed:	20 K meters/hour
Temperature:	31°C
Temperature profile:	Lapse
Cloud cover:	Hazy - no clouds

Depth of blast below grade level:	43 meters
Total charge of blast:	3954 K grams
Maximum charge per delay:	317.5 K grams/delay
Number of holes:	6
Depth of holes:	43 meters
Number of delays:	24
Time between delays:	40, 100, 120 or 150 mseconds
Total time of blast:	-
Blast face orientation:	North-Northeast

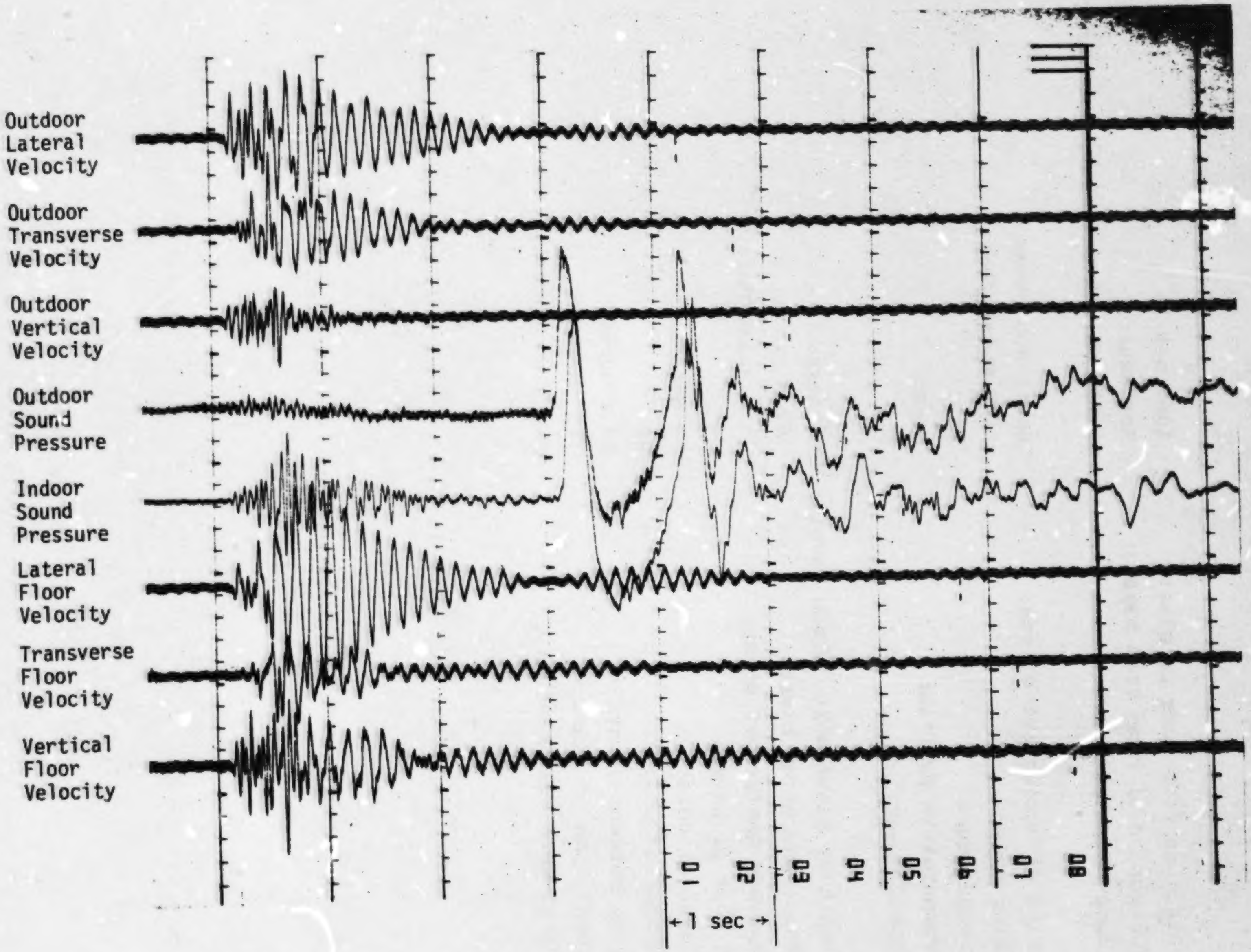

Fig. B-7. Oscillograph Record of Blast No. 7

Quarry Blast No. 8

Distance from home to blast: 1067 meters
Direction of home from blast: Northeast
Home construction: 1 floor with basement, wood frame

Wind direction out of the: South-Southwest
Wind speed: 24 K meters/hour
Temperature: 26°C
Temperature profile: Lapse
Cloud cover: 50%

Depth of blast below grade level: 45 meters
Total charge of blast: 762 K grams
Maximum charge per delay: 31 K grams/delay
Number of holes: 14
Depth of holes: 10 meters
Number of delays: 28
Time between delays: 14 mseconds
Total time of blast: 378 mseconds
Blast face orientation: East

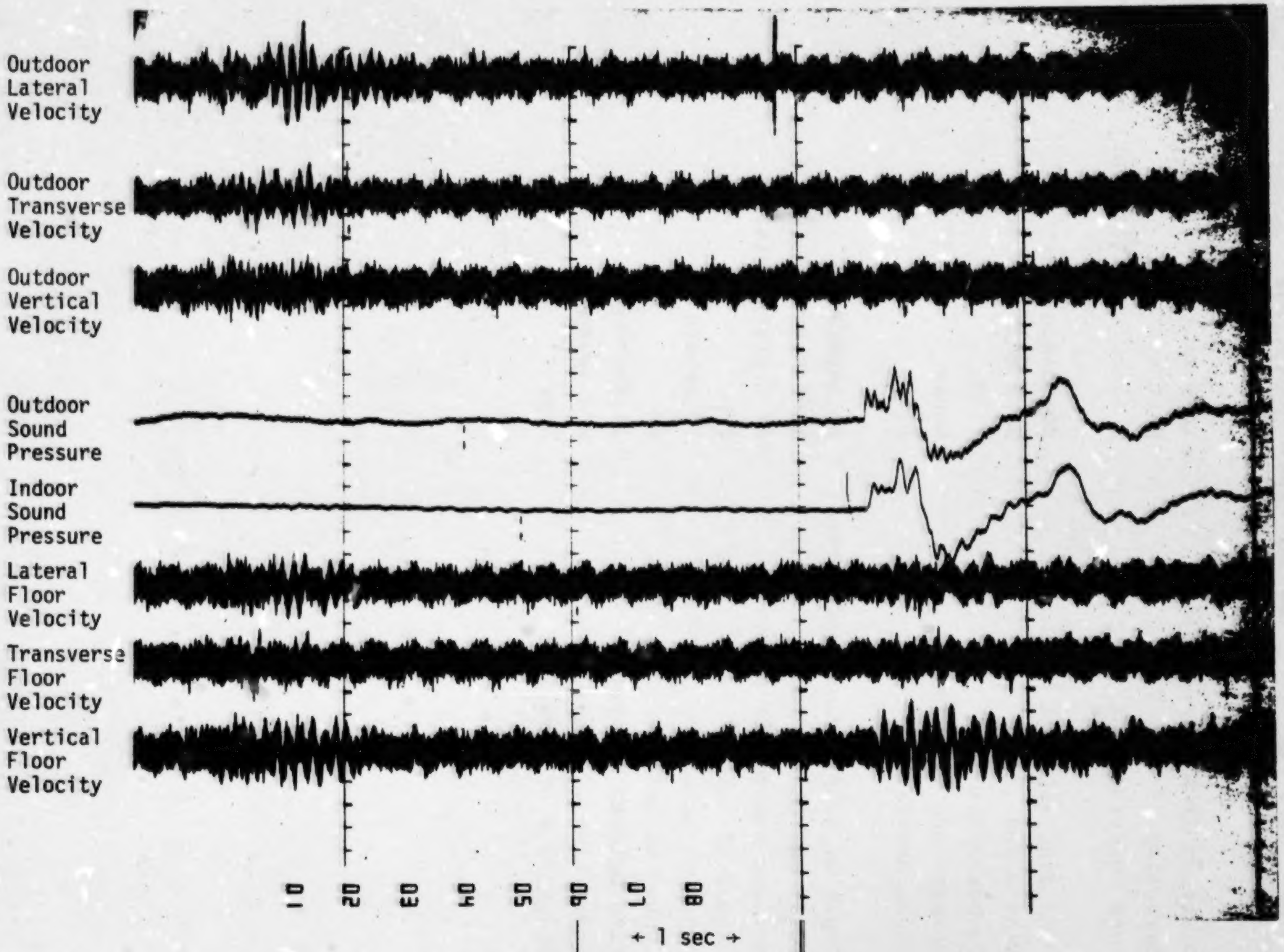

Fig. B-8. Oscillograph Record of Blast No. 8

Quarry Blast No. 9

Distance from home to blast: 1006 meters
Direction of home from blast: Northeast
Home construction: 1 floor with basement, wood frame

Wind direction out of the: South-Southwest
Wind speed: 24 K meters/hour
Temperature: 27°C
Temperature profile: Lapse
Cloud cover: 100%

Depth of blast below grade level: 45 meters
Total charge of blast: 1165 K grams
Maximum charge per delay: 61 K grams/delay
Number of holes: 17
Depth of holes: 10 meters
Number of delays: 17
Time between delays: 14 mseconds
Total time of blast: 238 mseconds
Blast face orientation: East

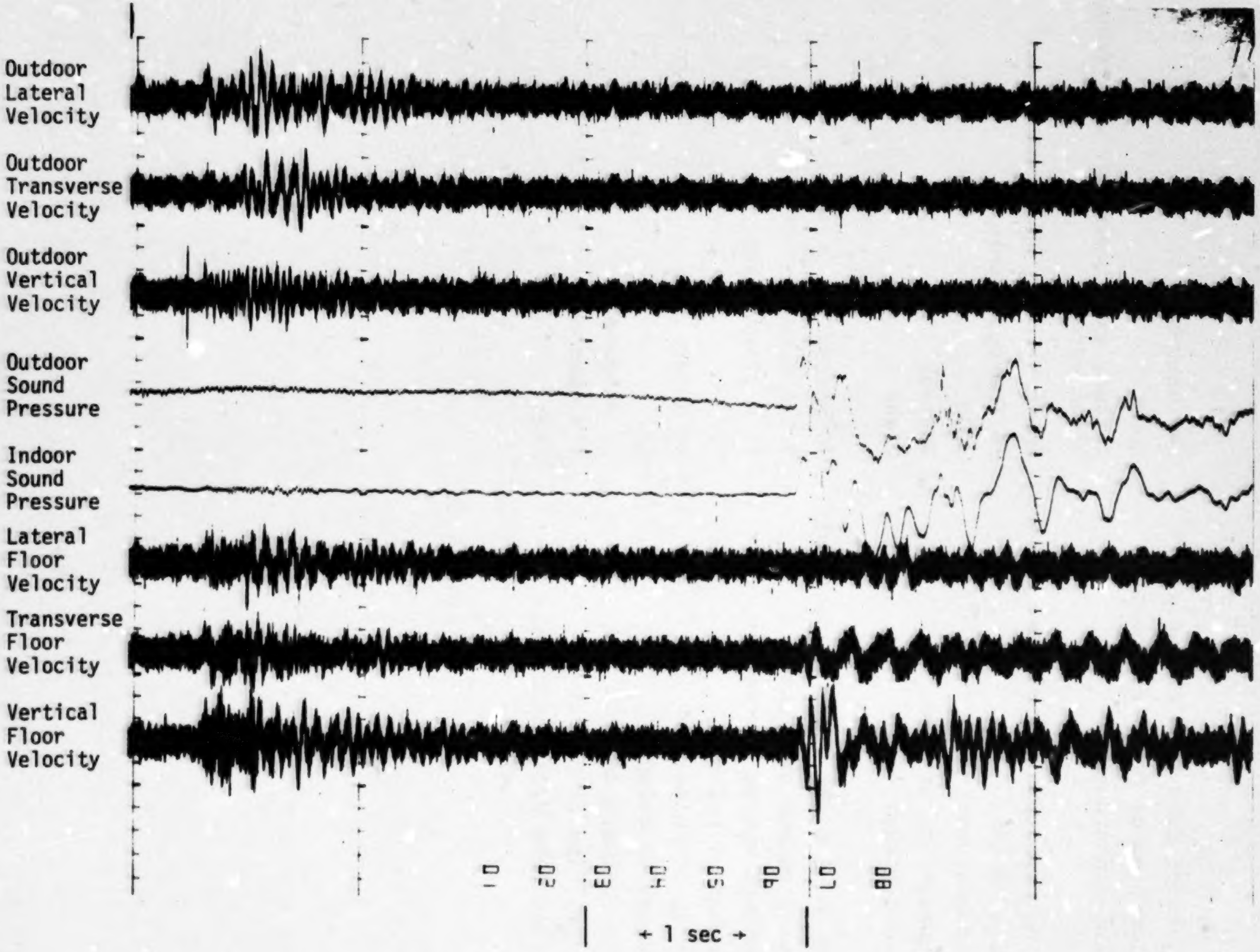

Fig. B-9. Oscillograph Record of Blast No. 9

Quarry Blast No. 10

Distance from home to blast:	646 meters
Direction of home from blast:	North
Home construction:	1 floor with basement, wood frame brick veneer
Wind direction out of the:	South
Wind speed:	16 K meters/hour
Temperature:	22°C
Temperature profile:	Neutral
Cloud cover:	Clear
Depth of blast below grade level:	70 meters
Total charge of blast:	911 K grams
Maximum charge per delay:	31 K grams/delay
Number of holes:	17
Depth of holes:	10 meters
Number of delays:	34
Time between delays:	14 mseconds
Total time of blast:	462 mseconds
Blast face orientation:	East

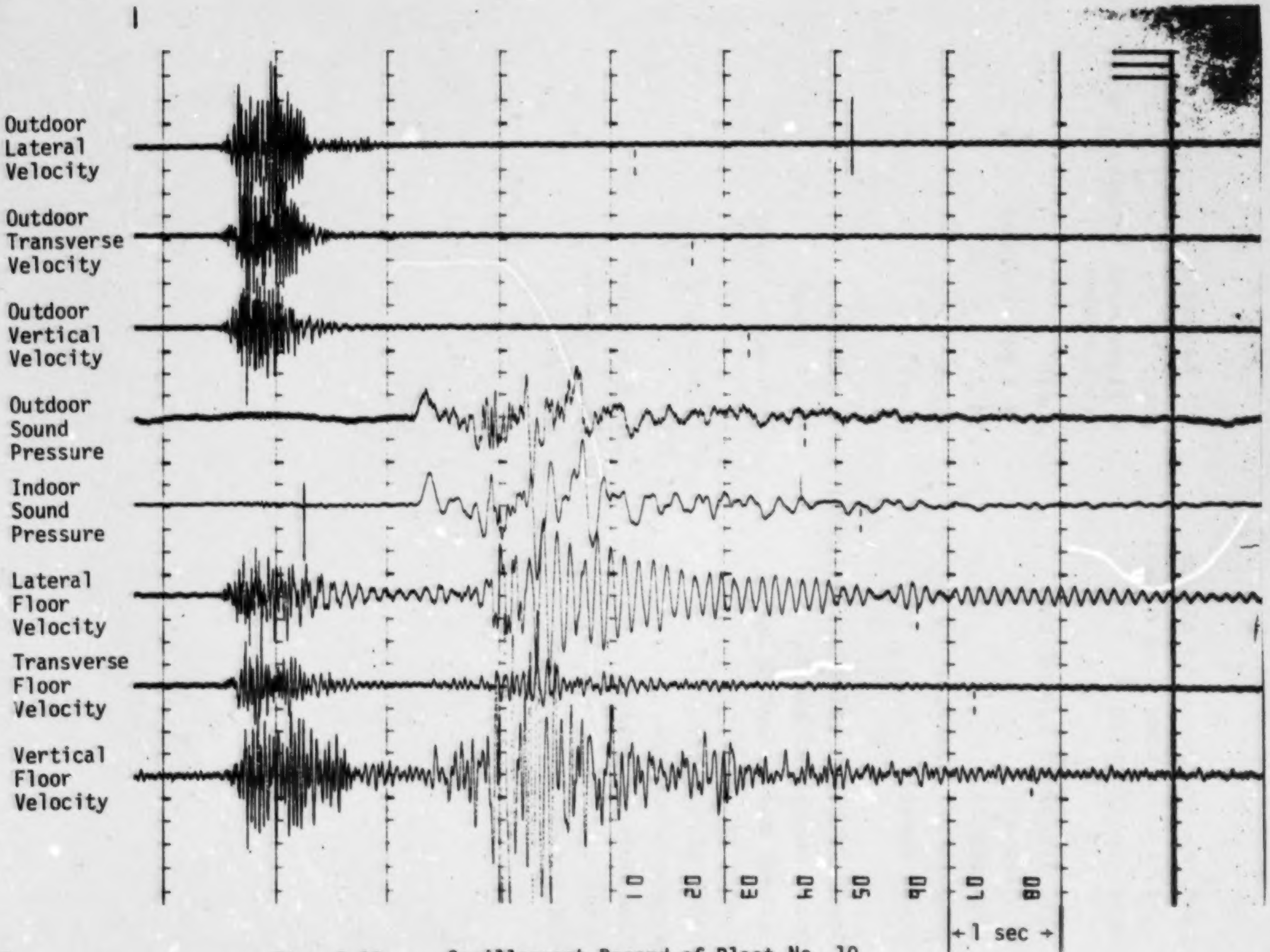

Fig. B-10. Oscillograph Record of Blast No. 10

Quarry Blast No. 11

Distance from home to blast:	701 meters
Direction of home from blast:	North
Home construction:	1 floor with basement, wood frame, brick veneer
Wind direction out of the:	South
Wind speed:	24 K meters/hour
Temperature:	24°C
Temperature profile:	Lapse
Cloud cover:	Clear
Depth of blast below grade level:	70 meters
Total charge of blast:	530 K grams
Maximum charge per delay:	31 K grams/delay
Number of holes:	10
Depth of holes:	10 meters
Number of delays:	19
Time between delays:	14 mseconds
Total time of blast:	266 mseconds
Blast face orientation:	Northeast

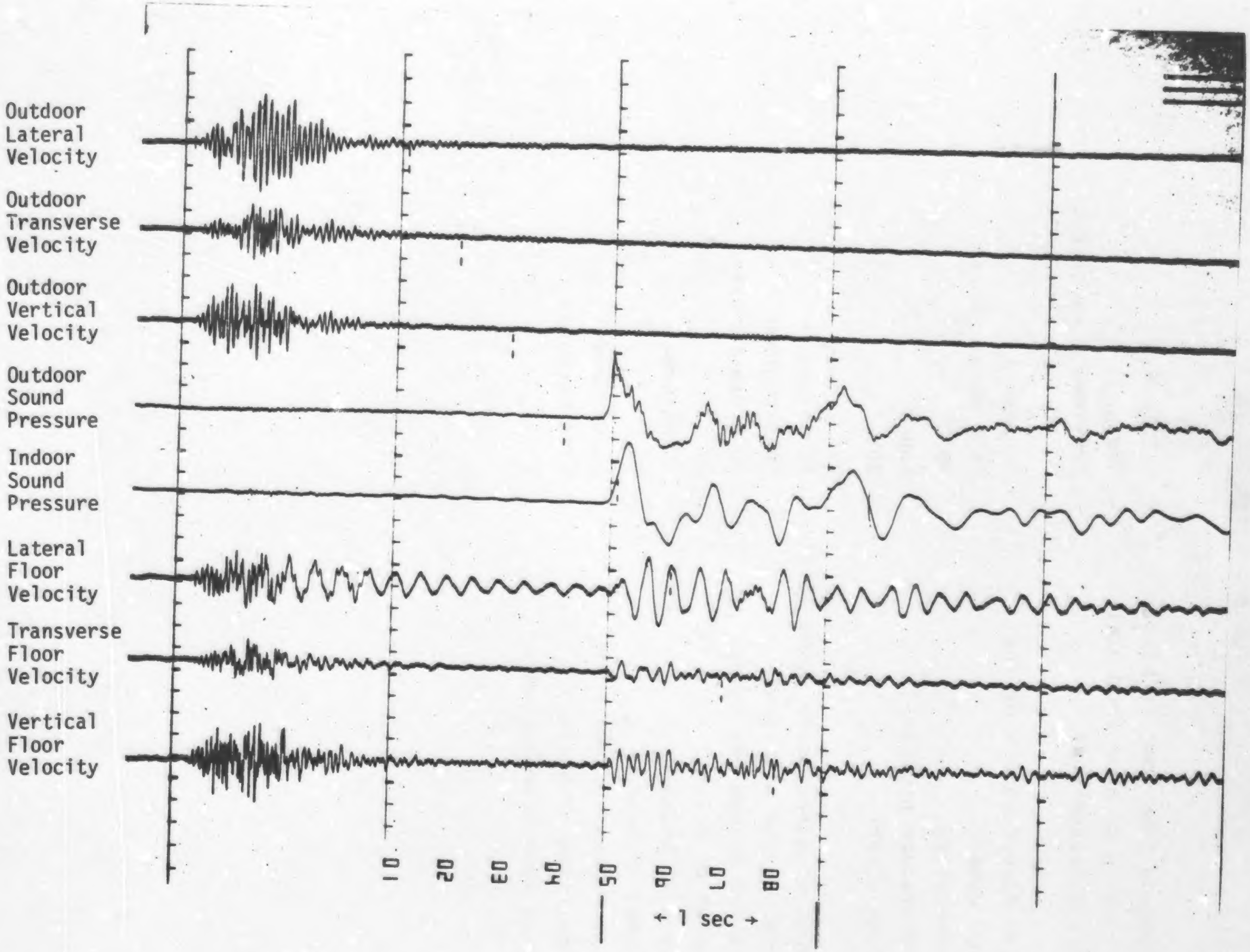

Fig. B-11. Oscillograph Record of Blast No. 11

Quarry Blast No. 12

Distance from home to blast:	701 meters
Direction of home from blast:	North
Home construction:	Tri-level, wood frame, brick veneer
Wind direction out of the:	Southwest
Wind speed:	16 K meters/hour
Temperature:	26°C
Temperature profile:	Lapse
Cloud cover:	20%
Depth of blast below grade level:	81 meters
Total charge of blast:	3039 K grams
Maximum charge per delay:	30 K grams/delay
Number of holes:	99
Depth of holes:	30 meters
Number of delays:	99
Time between delays:	14 mseconds
Total time of blast:	1372 mseconds
Blast face orientation:	Up

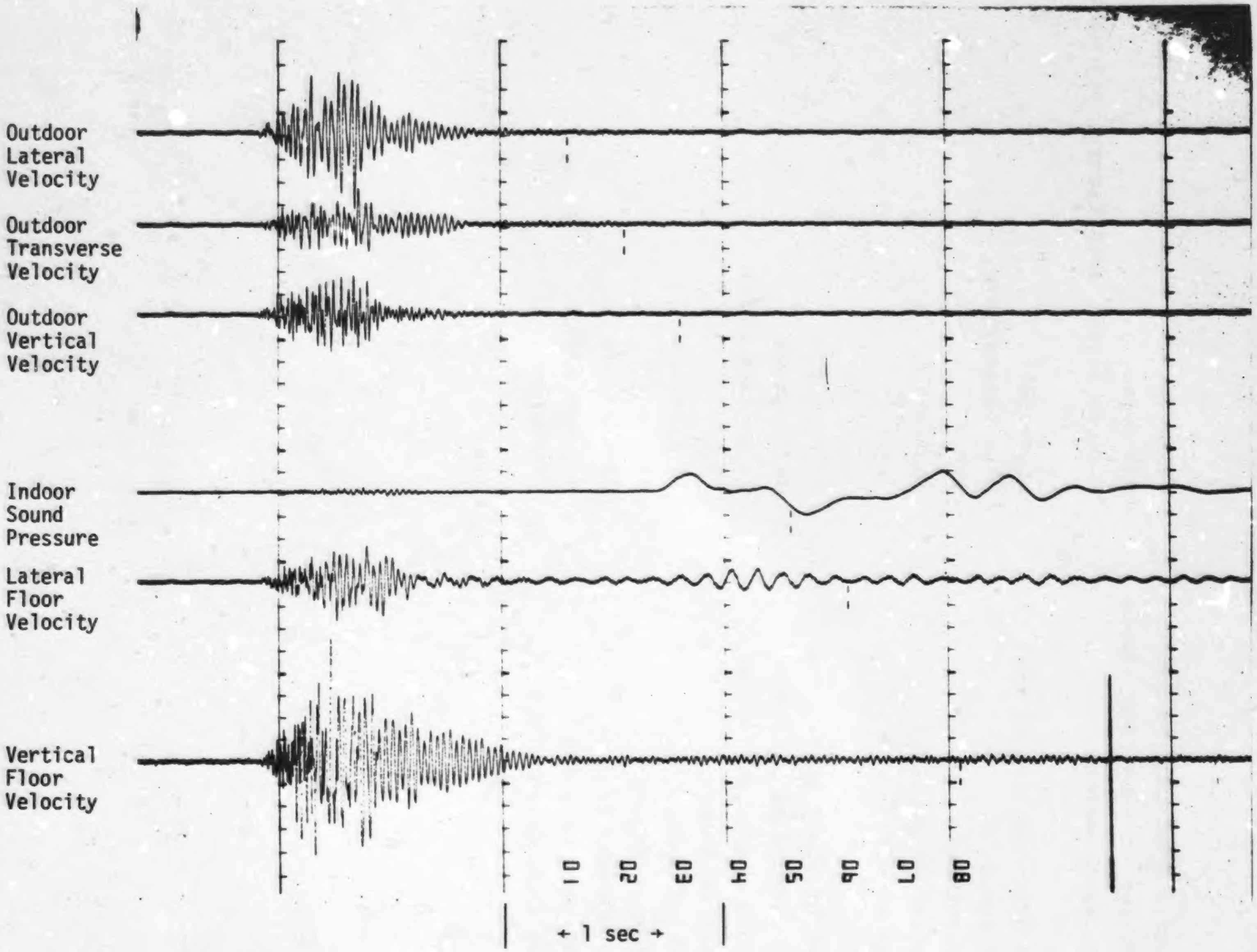

Fig. B-12. Oscillograph Record of Blast No. 12

Quarry Blast No. 13

Distance from home to blast: 610 meters
Direction of home from blast: Northeast
Home construction: 2-story brick, wood floors, basement

Wind direction out of the: Southwest
Wind speed: 24 K meters/hour
Temperature: 23°C
Temperature profile: Neutral
Cloud cover: Clear

Depth of blast below grade level: 31 meters
Total charge of blast: 882 K grams
Maximum charge per delay: 31 K grams/delay
Number of holes: 11
Depth of holes: 15.5 meters
Number of delays: 33
Time between delays: 25 mseconds
Total time of blast: 408 mseconds
Blast face orientation: Northwest

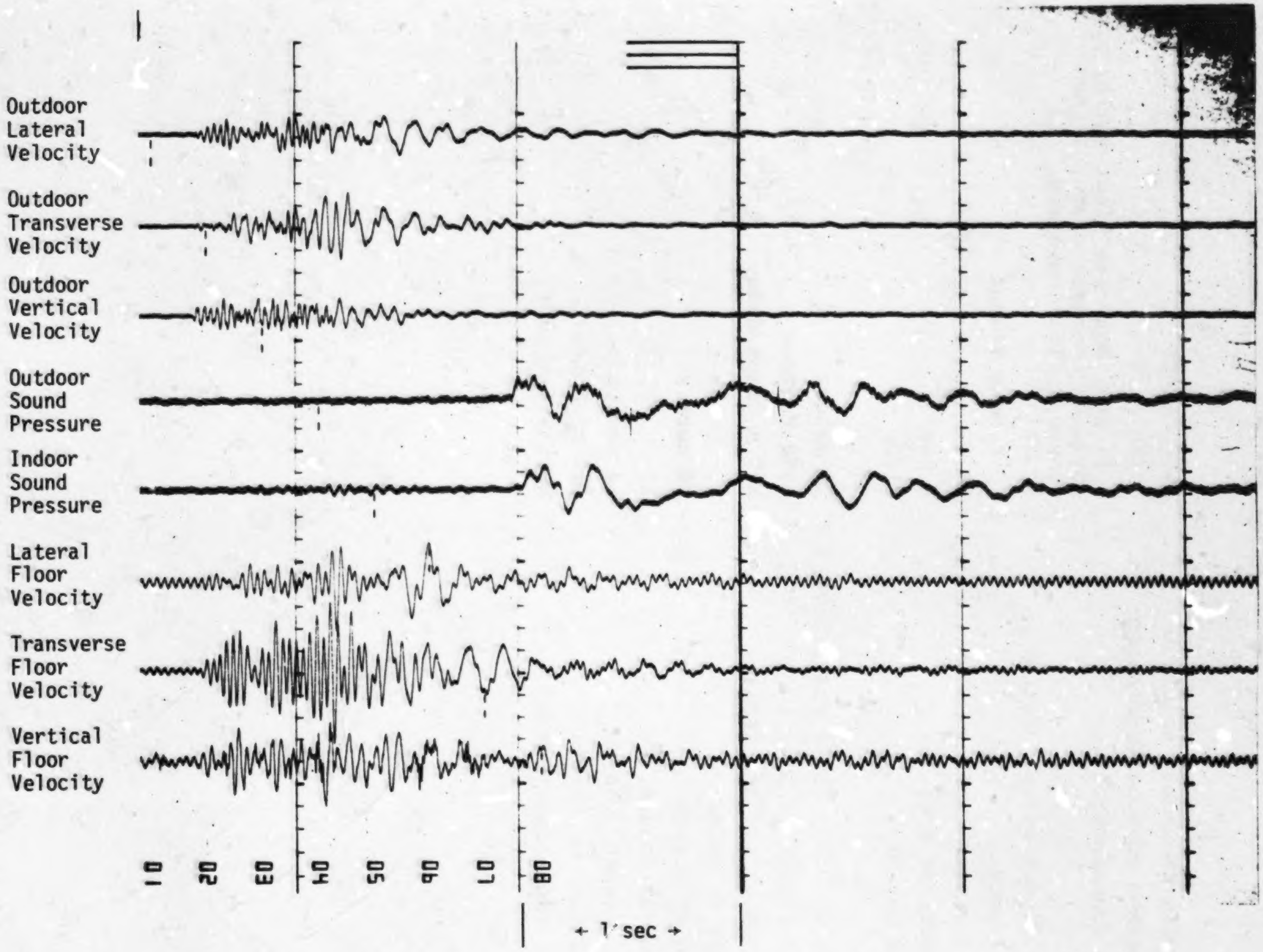

Fig. B-13. Oscillograph Record of Blast No. 13

Quarry Blast No. 14

Distance from home to blast: 1600 meters
Direction of home from blast: North
Home construction: 2 floors, concrete block walls, prestressed concrete slabs, 3-inch concrete floor covering
Wind direction out of the: South
Wind speed: 20 K meters/hour
Temperature: 18°C
Temperature profile: Lapse
Cloud cover: Clear

Depth of blast below grade level: 30 meters
Total charge of blast: 2555 K grams
Maximum charge per delay: 227 K grams/delay
Number of holes: 4
Depth of holes: 30 meters
Number of delays: 16
Time between delays: 14 mseconds
Total time of blast: 210 mseconds
Blast face orientation: North-Northeast

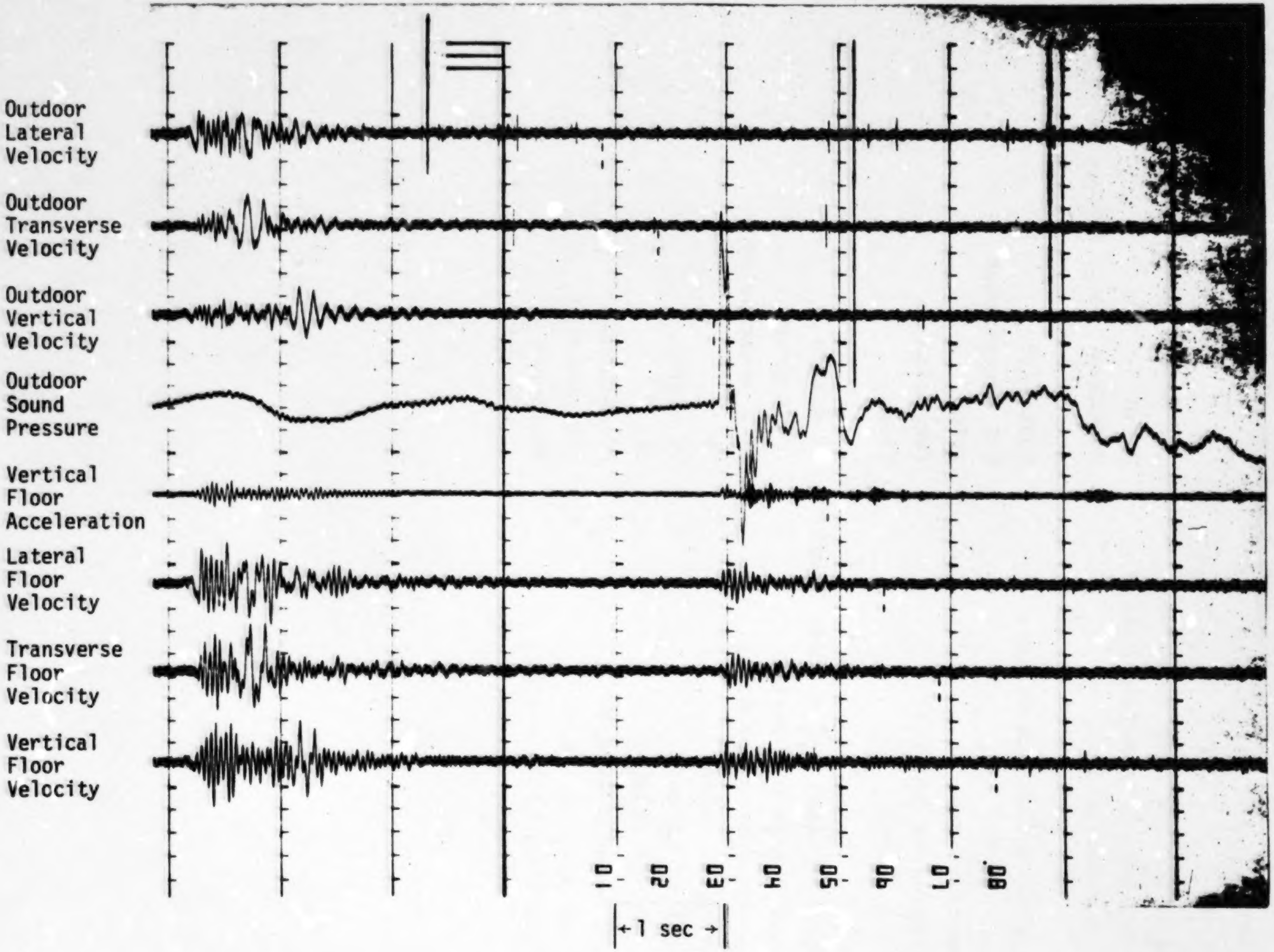

Fig. B-14. Oscillograph Record of Blast No. 14

Quarry Blast No. 15

Distance from home to blast: 762 meters
Direction of home from blast: North
Home construction: Tri-level, wood frame, brick veneer

Wind direction out of the: Southeast
Wind speed: 8 K meters/hour
Temperature: 11°C
Temperature profile: Inversion
Cloud cover: Clear

Depth of blast below grade level: 45 meters
Total charge of blast: 740 K grams
Maximum charge per delay: 32 K grams/delay
Number of holes: 14
Depth of holes: 10 meters
Number of delays: 28
Time between delays: 14 mseconds
Total time of blast: 378 mseconds
Blast face orientation: Northeast

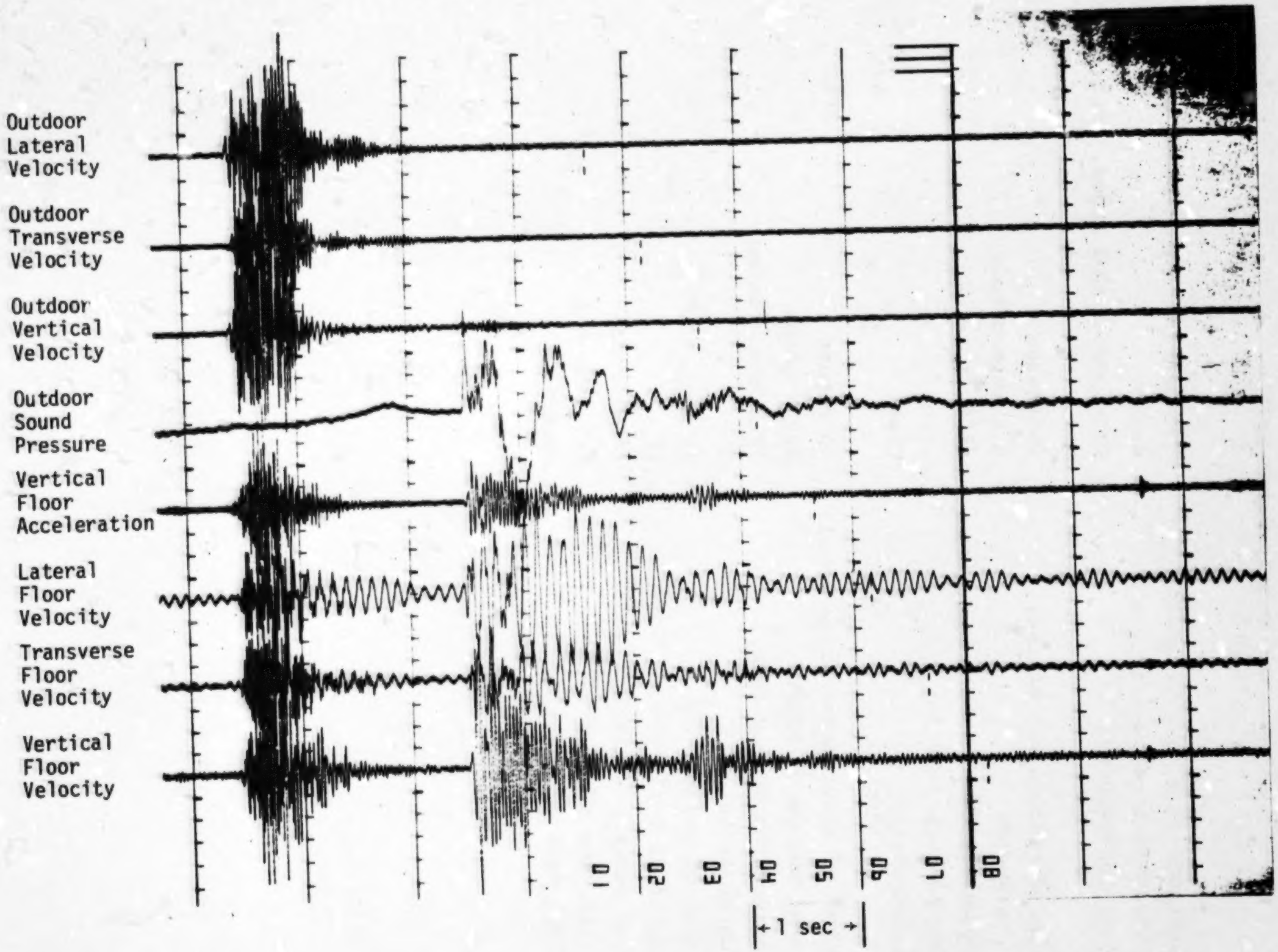

Fig. B-15. Oscillograph Record of Blast No. 15

Quarry Blast No. 16

Distance from home to blast: 716 meters
Direction of home from blast: North
Home construction: Tri-level, wood frame, brick veneer

Wind direction out of the: Southeast
Wind speed: 8 K meters/hour
Temperature: 16°C
Temperature profile: Lapse
Cloud cover: Clear

Depth of blast below grade level: 45 meters
Total charge of blast: 529 K grams
Maximum charge per delay: 32 K grams/delay
Number of holes: 8
Depth of holes: 10 meters
Number of delays: 16
Time between delays: 14 mseconds
Total time of blast: 210 mseconds
Blast face orientation: Northeast

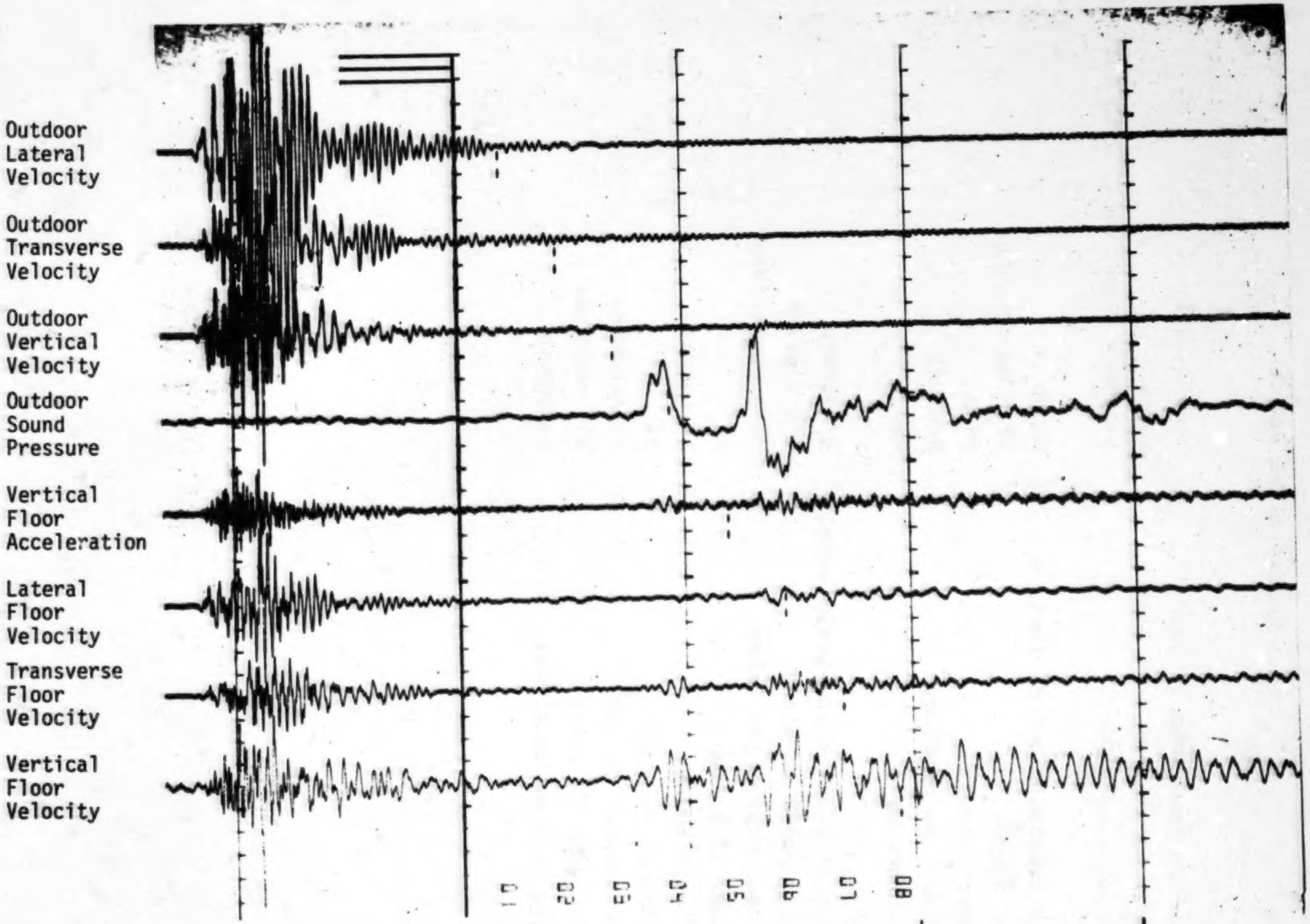

Fig. B-16. Oscillograph Record of Blast No. 16

Quarry Blast No. 17

Distance from home to blast: 1067 meters
Direction of home from blast: North
Home construction: 1 floor, wood frame, with basement

Wind direction out of the: South
Wind speed: 16 K meters/hour
Temperature: 16°C
Temperature profile: Neutral
Cloud cover: Clear

Depth of blast below grade level: 45 meters
Total charge of blast: 579 K grams
Maximum charge per delay: 31 K grams/delay
Number of holes: 13
Depth of holes: 10 meters
Number of delays: 26
Time between delays: 14 mseconds
Total time of blast: 350 mseconds
Blast face orientation: Southeast

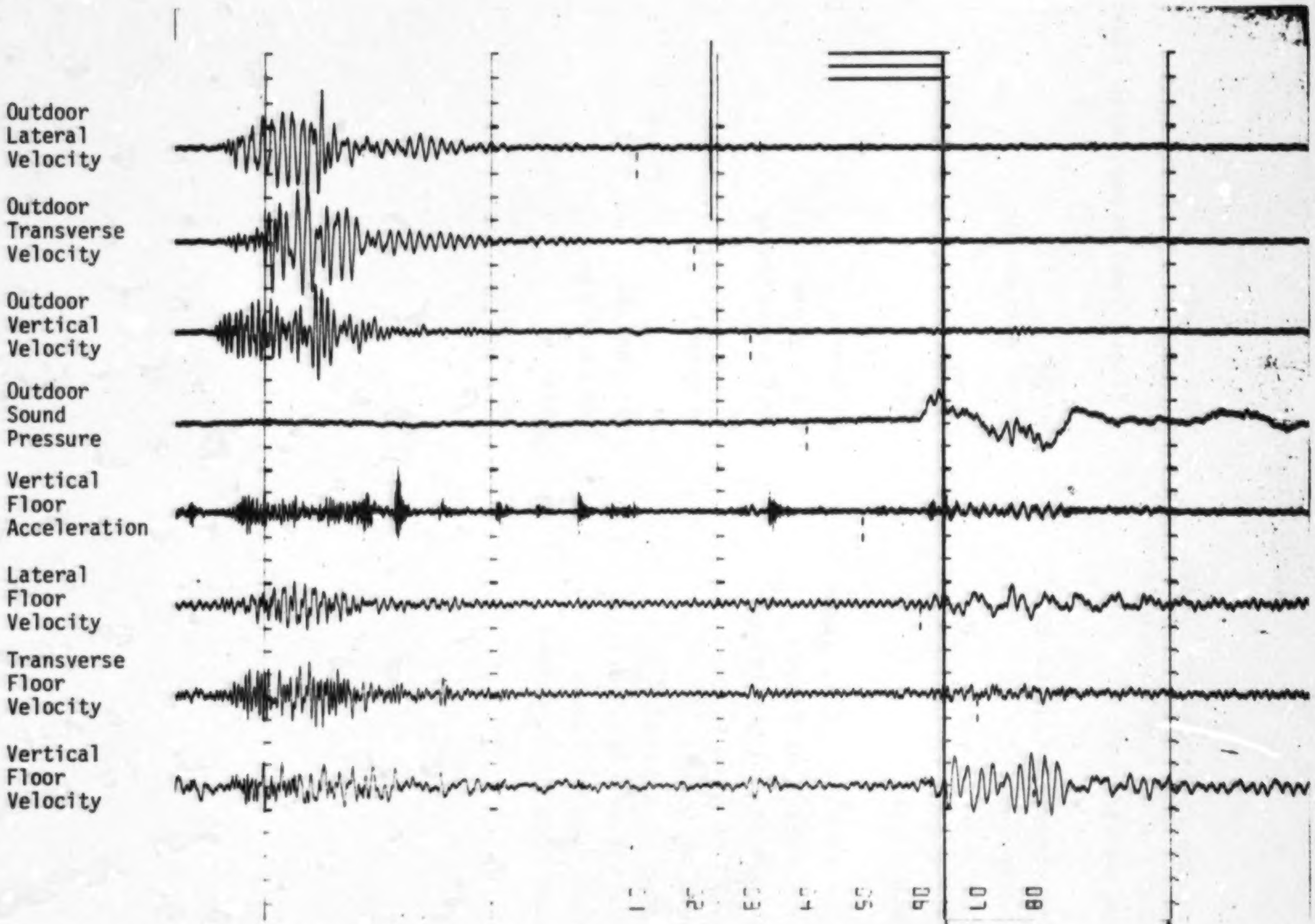

Fig. B-17. Oscillograph Record of Blast No. 17

Quarry Blast No. 18

Distance from home to blast: 1128 meters
Direction of home from blast: North
Home construction: 1 floor, wood frame, with basement

Wind direction out of the: South
Wind speed: 24 K meters/hour
Temperature: 21°C
Temperature profile: Lapse
Cloud cover: Clear

Depth of blast below grade level: 45 meters
Total charge of blast: 419 K grams
Maximum charge per delay: 31 K grams/delay
Number of holes: 10
Depth of holes: 10 meters
Number of delays: 20
Time between delays: 14 mseconds
Total time of blast: 266 mseconds
Blast face orientation: East

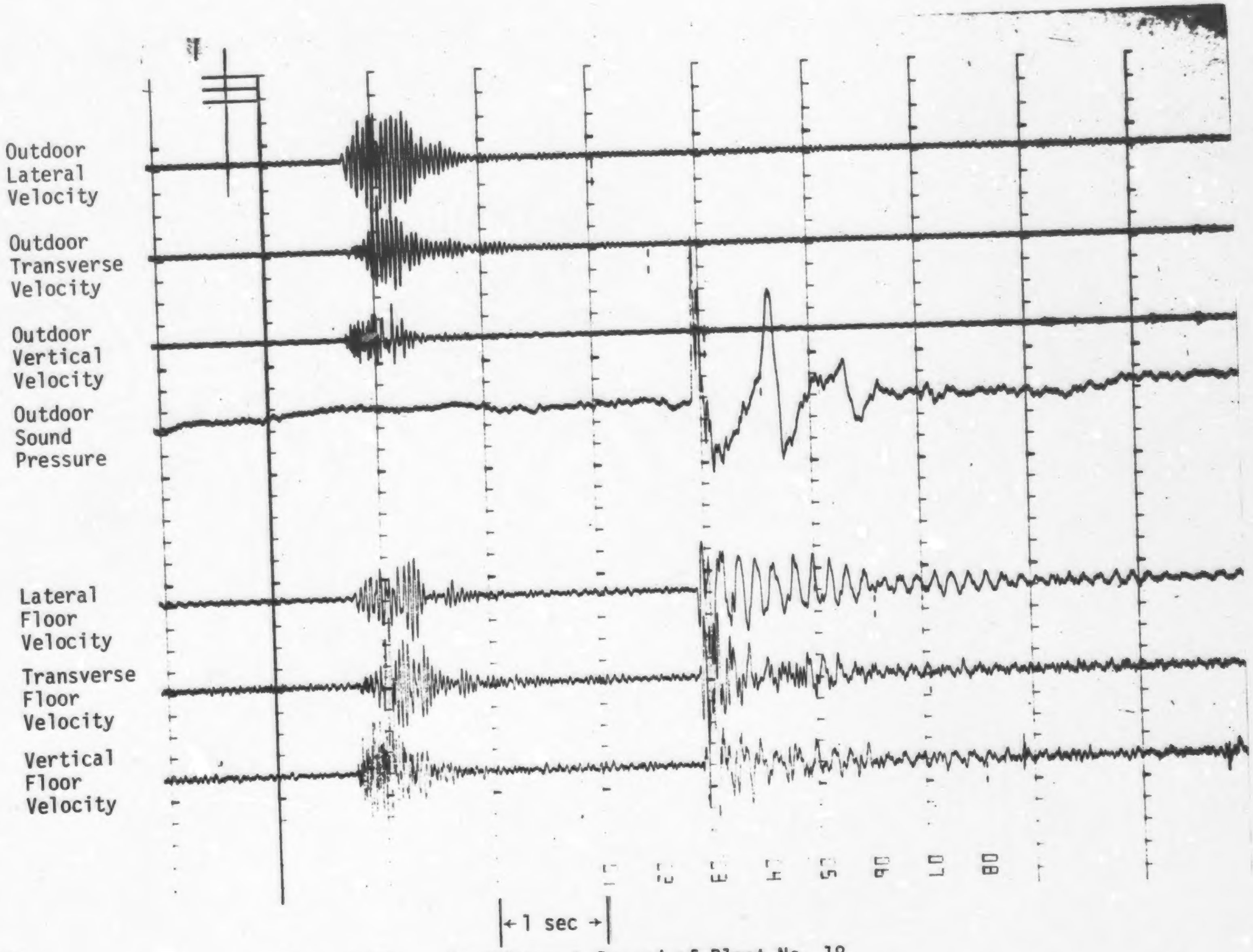

Fig. B-18. Oscillograph Record of Blast No. 18